Supporting Information

Rodents monitor their error in self-generated duration on a single trial basis

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S1. Schematic of a trial structure during training

(A) Schematic of a trial structure on duration and precision training trials. Task events are depicted in sequence from the top to bottom. They differ along the TP-axis (color bar with red, green, and orange colors) and show different scenarios, in single trials, that were determined by rats’ performance on TP. An inter-trial-interval (ITI) was the last event in a single trial sequence. See Methods: Duration and precision for further explanation.

(B) Schematic of a trial structure on error monitoring training trials. See Methods: Error monitoring training for further explanation.

(C) Schematic of pretraining and training procedure.

Supplementary Figure 1. Trial structure during training.

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(B) Schematic of a trial structure on error monitoring training trials. See Methods: Error monitoring training for further explanation.

(C) Schematic of pretraining and training procedure.
**S2** Time Production distributions for HOLD and PRESS groups

![Graph showing time production distributions for HOLD and PRESS groups](image)

**Supplementary Figure 2.** Time Production distributions for HOLD and PRESS groups displayed in Fig. 1. Premature, impulsive responses were removed from the plot to accentuate performance of interest around 3.2 s target duration.

**S3** Performance in Time Production differs between HOLD and PRESS groups (related to figure 1B)

In the time production task (Fig. 1), animals had to produce time intervals by making two presses spaced by the minimum amount of time (PRESS) or hold pressed a lever (HOLD) for a minimum amount of time T (T = 3.2s) in order to get access to a reward. All rats were able to produce the required time interval T, as TP distributions for all rats peaked after T (Fig. 2a). The HOLD group was more accurate and precise than the PRESS group (Fig. 2B), which was evident in a model comparing mean and standard deviation of TP between the two groups across all sessions (β = 0.11, t(551) = 8.86, SE = 0.012, p < 10^{-9}; β = 0.05, t(553) = 7.2, SE = 0.007, p < 10^{-9}, respectively). Despite this difference, but consistent with scalar variability in duration reproduction tasks (Jazayeri & Shadlen 2010), both groups showed increased variability with increasing mean TP (Supp. Fig. 3). This was confirmed in a regression model predicting standard deviation of TP with mean TP (β = 0.28, t(586) = 15.4, SE = 0.18, p < 10^{-14}). The addition of a group factor to the model was not justified (ΔAIC = 0.3, p = 0.155), suggesting that scalar variability was preserved in both groups in a similar form (Supp. Fig. 3).
Supplementary Figure 3. For each session and each rat, $\mu$(TP) is plotted against $\sigma$(TP) across sessions. Colored lines depict the regression fits for individual rats. Both panels contain inset plots showing a fit of one example rat.
**RT reflects the prospect of larger reward**

As an indirect measure of temporal error monitoring, we analyzed reaction times (RT). We hypothesized that RTs should be sensitive to reward anticipation based on reward prospect. To assess the possibility of error monitoring in rats, the animals were trained to associate TP accuracy (small error: TP_{SE} trials vs large error: TP_{LE} trials) with reward delivery (TP_{SE-2p} and TP_{LE-1p} trials) or its absence (TP_{SE-0p} and TP_{LE-0p} trials) in one of the two ports. The prospect of reward was indicated to animals, after TP was terminated, by a light cue in one of the two ports. To check if reward will indeed be delivered on any given trial, animals were required to first visit a port. Only upon the port visit did reward delivery or its absence become apparent to the animal. From the animal’s perspective, light cue to a particular port only indicates the delivery side. However, if rats are sensitive to temporal errors, RTs should be related to the accuracy of TPs, as classical work has shown that rats respond faster when expecting larger rewards (Rosenbaum, 1951). Indeed, if rats produced accurate TP_{SE}, their RT to the light cue in a port associated with 2 pellets should be more rapid than RTs following the production of less accurate TP_{LE}, as 0 pellet would then be expected in that port. The opposite dependence should hold for the other port (1 pellet port). This was evident in the relative RTs comparing rewarded to unrewarded trials in a given port (Supp. Fig. 4A; RT TP_{LE-1p} - RT TP_{SE-0p} (dark red); RT TP_{SE-2p} - RT TP_{LE-0p} (green), 1-pellet and 2-pellets port, respectively). The majority of rats responded faster to a light cue on rewarded trials than on the non-rewarded trials in each port. This effect was confirmed with a mixed model testing differences between the rewarded and unrewarded trials. A significant intercept in the model indicated that the RT difference was smaller than zero ($\beta = -0.018$ s) showing that RTs were faster on trials with the reward prospect ($SE = 0.008$, $t(34) = -2.11$, $p = 0.043$). In line with the reward prospect interpretation, rats responded also faster when reward prospect was larger (2p vs 1p), which was evident as a significant factor of port type in the model (1p vs 2p; $\beta = -0.051$, $SE = 0.009$, $t(1127) = -5.35$, $p < 10^{-6}$). The shortening of RT in anticipation of a larger reward prospect strongly suggests that rats may monitor their temporal errors.

**Supplementary Figure 4.** Rats reacted faster to larger subjective internally-based reward prospect.
(A) Data points from one column correspond to one rat. Each data point shows a reaction time difference between rewarded and unrewarded trials for 1p port (dark red; TPLE-1p – TPSE-0p) and 2p port (green; TPSE-2p – TPLE-0p). A majority of rats reacted faster to rewarded trials as evident in negative values. Additionally, reaction time difference was larger for 2p trials.

(B) RT on test-trials indicated choice behavior. Each individual data point shows a reaction time in training-trials (no choice) and test-trials (choice available). Rats showed longer RT during test-trials than during the training-trials ($\beta = 0.14$, $SE = 0.011$, $t(1163) = 9.54$, $p < 10^{-15}$), indicating expression of choice behavior as opposed to random responding.

**55. RT reflects the prospect of larger reward**

To assess whether rats used previous trial outcomes, we fitted the model that included current TP and previous TPs, or previous rewards (RH) up to 15 trials back (n-15). Indeed, the estimated odds showed that previous rewards contributed to rats’ choices (Supp Fig. 5a; n=0: $\beta = 2.87$, $SE = 0.083$, $z(18224) = 34.27$, $p < 10^{-15}$; n-1: $\beta = 0.25$, $SE = 0.031$, $z(18224) = 8.02$, $p < 10^{-14}$; see Supp Table 2), but with clear evidence for the strongest contribution of current TP. A similar pattern of results was obtained when current TPs were fitted together with previous TPs (Supp Fig. 4; n=0: $\beta = 2.82$, $z(18205) = 33.71$, $p < 10^{-15}$; n-1: $\beta = 0.51$, $z(18205) = 8.59$, $p < 10^{-15}$; see Supp Table 3).

**Supplementary Figure 5A.** Results of GLMM fit including current TP and reward history (RH) incorporated as rewards received on up to 15 previous trials. The formula in the plot shows specification of fixed terms in the GLMM. Asterisks indicate significant terms. Error bars display confidence intervals of estimated effects.
Supplementary Figure 5B. Results of GLMM fit including current TP and 15 previous trials as a proxy for reward history. As opposed to Supp. Fig. 4A where amount of reward was used, here TP were used. The formula in the plot shows specification of fixed terms in the GLMM. Asterisks indicate significant terms. Error bars display confidence intervals of estimated effects.

Supplementary Figure 6. Results of GLMM fit including current TP and running average of last 10, 20, 30 TPs. TP history predictors were computed separately for rewarded (A) and unrewarded trials (B). Significant model terms indicate that rats keep track of temporal errors on current TP as well as TP history.
Supplementary Figure 7. Each panel depicts reward history (RH) traces for individual rats. Each line originates from a single experimental session.

**S8 HOLD and PRESS groups keep track of temporal errors and reward history differently**

To understand what behavioral features are related to monitoring of temporal errors, we hypothesized that HOLD and PRESS groups may differently utilize current temporal errors and previous trial information such as reward history. We hypothesized that owing to its wider TP distribution (Fig. 1B), the PRESS group could achieve better choice performance (Fig. 2). To test whether PRESS and HOLD groups achieved their choice behavior differently, we re-fitted the model including TPn and the strongest factors reflecting previous trial information, that is $\mu_{RH0}$ and $\mu_{TP30}$ (see Fig. 3BC). We added an interaction with group factor to each predictor (Supp Fig. 7). As hypothesized, we found that HOLD and PRESS groups relied differently on current trial TP (Fig S6A, $TP_n$ * Group: $\beta = 0.33$, $SE = 0.046$, $z(16426) = 7.21$, $p < 10^{-12}$; Fig S6B, $TP_n$ * Group: $\beta = 0.53$, $SE = 0.18$, $z(16965) = 2.97$, $p = 0.003$) and previous trial information (Fig S6A, $\mu_{RW10}$ * Group: $\beta = -0.09$, $SE = 0.047$, $z(16426) = -1.97$, $p = 0.049$; Fig S6B, $\mu_{TP30}$ * Group: $\beta = -1.08$, $SE = 0.34$, $z(16965) = -3.12$, $p = 0.002$). Notably the PRESS group tended to rely more on...
the current TP, whereas the HOLD group relied more on previous trial information (TP and reward history), suggesting that the nature of motor sequence and associated variability contributed differently to choice behavior. Nevertheless, both PRESS and HOLD groups still relied on the current trial TP.

Supplementary Figure 8. Results of GLMM fit including current TP and previous trial history. In conjunction with current TP, we tested $\mu_{RW10}$ (A) and $\mu_{TP30}$ (B).

S9 Behavioral variability and hunting behavior (related to figure 4C)

We considered a possibility that the hunting index could be affected by the degree of variability of a given rat, and that, as a result, it could affect the association between hunting and error monitoring. We addressed that concern in two ways. We verified that the addition of standard deviation of TP for each rat to the model including TP was not justified (Wald test: $W(1) = 0.03$, $p = 0.866$).

The other verification was based on the previous work in rat, monkey and humans indicating that reward magnitude calibrates performance variability on the next trial (Wang et al., 2019; Dhwale et al., 2019). We confirmed that TPs that followed TPSE-2p had smaller variability than TPs that followed TPLE-1p ($t(1009) = -4.13, p < 10^{-4}$; Supp. Fig. S9A). Given that we replicated the impact of variability in our data set, we compared TPs that followed a TPLE-1p - TPSE-2p sequence with those that followed a TPSE-2p - TPSE-2p sequence. TPs that followed these two types of sequences did not differ ($t(882) = -0.867, p = 0.39$; Supp. Fig. S9B). Together, these two analyses suggest that TP variance did not mediate the relationship between propensity of individual rats to monitor temporal error and to hunt for minimizing it.
Supplementary Figure 9. Behavioral variability and hunting behavior (related to figure 4C). (A) Standard deviation of TP preceded (n-1 trial) by 2p trials is smaller than those preceded by 1p trials. (B) Standard deviation of TP preceded by ‘1p -> 2p’ and ‘2p -> 2p’ trial sequences (n-2 and n-1) did not differ.
Supplementary Figure 10. The number of test-trials obtained per session per rat.

Supplementary Figure 11. 2p/1p ratios obtained per session per rat. The horizontal black line displays $\Theta$ threshold.
**Supplementary Tables**

| Group | Rat number | Wilcoxon test | p value | Session count > 55% |
|-------|------------|---------------|---------|---------------------|
| HOLD 1 | 96 | 4.4e-02 | 6 |
| PRES 1 | 810.5 | 7.6e-08 | 35 |
| HOLD 2 | 100 | 3.2e-03 | 3 |
| PRES 2 | 519 | 1.9e-06 | 21 |
| HOLD 3 | 595 | 3.8e-07 | 34 |
| PRES 3 | 820 | 3.7e-08 | 35 |
| HOLD 4 | 774 | 1.0e-06 | 24 |
| PRES 4 | 805 | 1.1e-07 | 31 |
| HOLD 5 | 754 | 3.9e-06 | 26 |
| PRES 5 | 775 | 8.1e-08 | 33 |
| HOLD 6 | 583 | 8.9e-05 | 23 |
| PRES 6 | 727 | 2.7e-06 | 25 |
| HOLD 7 | 811 | 7.3e-08 | 32 |
| PRES 7 | 695 | 2.3e-07 | 31 |
| HOLD 8 | 669.5 | 9.9e-05 | 24 |
| PRES 8 | 455 | 1.9e-03 | 18 |

Supplementary Table 1. Results of two-sided Wilcoxon test performed on test-trial accuracy for each rat separately. Test-trial accuracy on a single session served as a unit of observation for statistical testing. The last column displays the number of session where test-trial accuracy was above 55%.

| TP Lag (n) | Beta estimate | z value | p value |
|------------|---------------|---------|---------|
| 0          | 16.94         | 34.4    | 3.0e-259 |
| 1          | 1.64          | 8.51    | 1.7e-17  |
| 2          | 1.43          | 6.25    | 4.0e-10  |
| 3          | 1.14          | 2.36    | 1.8e-02  |
| 4          | 1.22          | 3.47    | 5.1e-04  |
| 5          | 1.23          | 3.68    | 2.3e-04  |
| 6          | 1.25          | 3.8     | 1.4e-04  |
| 7          | 1.18          | 2.84    | 4.5e-03  |
| 8          | 1.3           | 4.59    | 4.5e-06  |
| 9          | 1.26          | 4.04    | 5.4e-05  |
| 10         | 1.1           | 1.65    | 9.8e-02  |
| 11         | 1.28          | 4.3     | 1.7e-05  |
| 12         | 1.24          | 3.88    | 1.0e-04  |
| 13         | 1.14          | 2.36    | 1.8e-02  |
| 14         | 1.3           | 4.61    | 4.0e-06  |
**Supplementary Table 2.** Detailed results of GLMM fit including current TP and rewards received on 15 previous trials. The values correspond to the data visualized in Supp. Fig. 4A.

| TP Lag (n) | Beta estimate | z value | p value  |
|-----------|---------------|---------|----------|
| 0         | 17.69         | 34.27   | 2.4e-257 |
| 1         | 1.28          | 8.02    | 1.1e-15  |
| 2         | 1.24          | 6.96    | 3.5e-12  |
| 3         | 1.19          | 5.53    | 3.3e-08  |
| 4         | 1.29          | 8.35    | 6.6e-17  |
| 5         | 1.29          | 8.25    | 1.5e-16  |
| 6         | 1.39          | 10.88   | 1.5e-27  |
| 7         | 1.42          | 11.4    | 4.1e-30  |
| 8         | 1.44          | 11.81   | 3.4e-32  |
| 9         | 1.38          | 10.54   | 5.9e-26  |
| 10        | 1.36          | 9.91    | 3.7e-23  |
| 11        | 1.35          | 9.86    | 6.3e-23  |
| 12        | 1.32          | 9.06    | 1.4e-19  |
| 13        | 1.26          | 7.52    | 5.5e-14  |
| 14        | 1.31          | 8.87    | 7.5e-19  |
| 15        | 1.14          | 4.16    | 3.1e-05  |

**Supplementary Table 3.** Detailed results of GLMM fit including current TP and 15 previous TPs as a proxy for reward history and produced intervals. The values correspond to the data visualized in Supp. Fig. 4B.