Reviewers' comments:

Reviewer #1: This manuscript by Wang et al. describes a novel rodent task for exploring explore-exploit decision making across varying "time horizons". Their approach is based on a similar task characterized humans in an earlier paper, and the current study includes further examination of human explore-exploit decisions on this task. The influence of relevant variables on task performance are described (though inferential statistics are scant), and this is supplemented with Bayesian model fitting to characterize parameters associated with two established heuristics for exploration: directed exploration (exploration threshold parameter) and random exploration (decision noise parameter). Like humans, rats performed the task well and were able to guide their choices by comparing recent information from guided trials with prior knowledge of possible outcomes. A major species difference was that humans increased their initial exploration of the unguided (unknown) option with time horizon (i.e., number of future opportunities to exploit feedback from guided and early choice trials), which represents a rational, directed exploration heuristic. Rats, instead, showed the reverse relationship, and additional data indicated that their exploratory behavior may have been driven in part by volatility in reward contingencies. Rats also appeared to show improved performance and less initial exploration when allowed to self-guided vs. being forced to sample one of the two response options. This is a really interesting study and the authors do a good job of highlighting the potential advantages and novel elements of this task versus other rodent tasks for measuring explore-exploit decision making. Despite some current issues (listed below), I believe the manuscript would be of interest to many in the field.  
  
1) The conceptual framework for the current study is not very well developed, particularly in the Introduction, which assumes quite a bit of readers. The main question at hand - i.e., how time horizon relates to explore/exploit decisions is not really discussed until late in the paper (in Discussion), which would make it difficult for readers to understand the purpose of experimental design parameters, as well as predictions about results. Also, much of the introduction lists limitations of existing reversal learning tasks but it is not very clear how the current approach will improve on this. For instance, without providing a clearer idea of the structure of the current task and how it relates to relevant decision making variables, it is not obvious why the current task does not have the same limitations. The current task also involves a 2-option choice with differential reward, so why is it better than reversal learning?

* We thank the reviewer for the criticism on the clarity of the conceptual framework. We have expanded the description of time horizon in the introduction and elaborated on how time horizon relates to exploration. The description of time horizon was made into a separate paragraph in the modified manuscript.
* We also modified the paragraph about the limitations of the reversal learning paradigm, and explicitly stated how our design addressed the limitations in the last paragraph of the introduction. Our task is better than the reversal learning approach mainly in the following ways:
  + Firstly, both good and bad outcomes should occur in exploration. However, in reversal learning, after the reversal point, “exploring” the previously suboptimal option will always lead to a better outcome. Exploration is confounded with simply abandoning a bad option. But in our design, exploring the unguided option can lead to both better or worse outcomes.
  + Secondly, it’s difficult to separate different drives and heuristics for exploration in reversal learning paradigms. To study directed exploration (uncertainty driven exploration) for example, there needs to be a difference in uncertainty between the two options. For reversal learning, this uncertainty difference is implicit in that the less chosen option has more uncertainty, since the less chosen option in reversal learning also usually has a lower estimated value, value and uncertainty are confounded in reversal learning. However, in our design both value and uncertainty are manipulated and independent from each other, allowing us to dissociate uncertainty from value and properly measure directed exploration.

2) There are very few statistical results provided. Instead, the Results consists of general descriptions of group level performance without evidence of the significance of findings. This is generally problematic but especially for subtle effects (e.g., constant vs. random reward differences in Fig 10; horizon effects on model parameter estimates in Figure 8; reference to horizon effect on switch in Fig 4D on p. 14).

We thank the reviewer for criticizing the statistical validity of our results. To address this, we added missing p-values throughout the results section of the manuscript. We reran all the analysis after incorporating suggestions from other comments of the reviewer (e.g. controlling for feeder preference). Here we highlight the main findings of the paper with statement of statistical significance.

* + - 1. (Similar to humans) Rats were able to use prior information to guide exploratory choices.

In figure 4C, rats were able to choose the high reward option at the first free choice (without knowing the reward of the unguided option) significantly above chance (p < 0.001 for H = 1 and 6, p = 0.01 for H = 15). They can only perform above chance if they have access to prior information.

* + - 1. (Similar to humans) Rats adapted the extent to which they explore based on the guided reward size. In figure 7C, Two-way ANOVA (Horizon x Guided reward) revealed a significant main effect of guided reward (p < 0.001).
      2. (Different than humans) Rats used less directed exploration (have lower thresholds) in long horizons.
         1. In Experiment 1(Figure 8), there is a significant main effect of horizon on the threshold parameter for humans (p < 0.001), but there is no significant effect of horizon on the threshold parameter for rats (p > 0.05). In other words, when different horizon conditions are done between sessions, we didn’t find a significant horizon effect on directed exploration.
         2. In Experiment 2(Figure 9), there is a significant main effect of horizon on the threshold parameter for rats (p < 0.001). There is also a significant main effect of horizon on the model-free p(explore) measure (p = 0.003). Together, we showed a significant horizon effect on directed exploration if rats experience both horizons within a session. (Note that the horizon conditions are always within-session for human experiments.)
      3. (Rats alone) Rats explored differently in self-guided exploration compared to cue-guided exploration. In Figure 11D, we showed that there is a significant main effect of nGuided (0 for self-guided vs 1 for cue-guided) on p(explore), p < 0.001.

For the particular figures that the Reviewers mentioned:

* + - 1. (Figure 10D, F) For random reward condition, we showed that there is a significant increase of both threshold (p < 0.01) and noise (p < 0.01) parameters compared to the constant reward condition.
      2. (Figure 8) See 3a above. We have added to figure 8 that the effect is non-significant.
      3. (Figure 4D) P(switch) at later trials (trial# 2-6 in H = 6 vs trial# 11-15 in H = 15) is significantly lower for H = 15 than H = 6 (p < 0.001).

3) Some additional methodological details should be provided or clarified. What volume were the sugar water drops? Were the rats food/water restricted? How many trials/games per session? Were rats trained through different phases at different rates based on performance? Were rewards ever symmetrical across options within games and if so how was this dealt with for analysis?

* The volume of sugar water drop was 0.15 microliter per drop.
* The rats were food restricted and were not water restricted.
* For Experiment 1, rats on average do 31.3 games and 125.3 trials per session for H = 1, rats on average do 13.5 games and 121.5 trials per session for H = 6, rats on average do 6.5 games and 123.4 trials for H = 15. On average, each rat completed 348.7 H = 1 games, 375.8 H = 6 games, and 170 H = 15 games.

For Experiment 2, rats on average do 25.62 games and 130.44 trials per session.

* Rats were trained through different phases at different rates during pretraining. We first train rats to associate light with reward, then they are trained to go to the homebase to trigger the lights at the reward feeders (first with reward at homebase, then remove the homebase reward), then they are trained to learn that two feeders give different amounts of rewards (first 0 vs 1 drops, then 1 vs 5 drops, then the full reward schedule).Rats went through these phases of pretraining at different rates based on performance. After pretraining, all rats performed 3 three experiments in the order: Experiment 1, Experiment 2 and then Experiment 3. We have added a paragraph describing pre-training in the manuscript.
* Rewards of the two options were generated independently using a MATLAB program for each game. So yes, rewards for two options can be identical (6.6% of all trials). These trials were included in all analysis that focuses on the 1st free choice (since rats only know the guided reward before making the first free choice, whether the unguided option has an identical value doesn’t really matter). These trials were excluded when doing analysis of later trials, this includes Figure 4, 5, 10AB, 11AB.

4) For Experiment 2, it was unclear exactly how H conditions were organized within session, though it seems to be the case that they were strictly alternated when confounded with home base. This should be in Methods. Also for this experiment, how were nG 0, 1, and 3 conditions organized (e.g., blocks of sessions, randomly across sessions).

* Horizons were strictly alternated in Experiment 2, for a given session, one of the homebase will always have H = 1 and the other will always have H = 6. For each session, a MATLAB program will pseudo-randomly make the homebase/horizon condition pairing. So Homebase A can be H = 1 for one session and H = 6 for another session.
* nG = 0,1,3 were run in blocks of sessions.

5) For the human task, does the schematic in Figure 3 represent actual task stimuli and procedures? For example, were subjects given a tally of past reward histories for all trials within a game? This should be indicated in Methods.

* The schematic in Figure 3 represents the actual task stimuli. Subjects were given a tally of past reward histories for all trials. We have added this information to the Methods.

6) Do the data presented in figures represent all the data from all relevant sessions or were they restricted to sessions after rats had time to learn about the new task contingencies? For example, rats presumably took some time to learn about the change in time horizon across blocks of sessions in Experiment 1. And the same goes for when they switched to the within-session analysis of horizon in Experiment 2, and the random task in Experiment 3. As noted by the authors, performance in the random task shows some clear carryover from the earlier phases of testing. This should be specified as good practice but also raises questions about species differences.

* We thank the reviewer for this useful suggestion. The data presented in the initial submission used all the data from all relevant sessions. In the current submission, we adopted the reviewer’s suggestion and presented results from analysis after excluding the transitioning sessions. In Experiment 1, we excluded 1 whole session after each transition of horizon conditions. In Experiment 2, we excluded the first session for each rat, and we excluded the first 2 games in each session (Although we have high/low pitch sound cues played at the homebases to help signal H = 6/H = 1 horizon condition respectively, in practice, it may take rats 1 full game to learn the associated horizon condition with each homebase). The exclusion did not change our results or conclusions in the paper.
* Experiment 3 was not essential to the main conclusions of this paper. Experiment 3 was carried out at the end of Experiment 2 to test how volatility might account for horizon-dependent changes in exploration in rats. Despite the possible carry-over effects, the fact that volatility changes both the decision noise parameter and the threshold parameter, and that only threshold changes across horizons in actual behavior, suggest that volatility may not be what’s driving the threshold specific horizon-dependent changes in rats.

7) Humans seem to have little trouble deploying a directed exploration strategy based on time horizon and guided choice feedback (reward size). They seem to explore the unguided option during the first free choice if there is any question about what the best option is, particularly when there is a long horizon to exploit that information. The authors state (p. 10) while showing similar early exploration, "it took longer for rats to switch back," referring to their persistent switching behavior in Fig 4 and 5. But these data are really able to get at this question precisely because they don't describe whether the switch is moving away or toward the guided choice. Given the rats' generally poorer performance and persistent tendency to switch within games, even with long horizons, suggests that they were switching back and forth from the best option. This is later discussed in the context of the random reward task, but the authors should avoid giving the wrong impression when discussion Fig 4 and 5.

This is a very good point. We split p(switch) into p(switch away) vs p(switch back). It looks like the difference between the “guided = good” option and the “guided = back” option occurs in the direction of switching back to the guided choice. On top of the persistent baseline switching in rats, rats do switch back from the unguided option (more than they switch away, when the guided option is objectively better) to the guided option up to trial #4 in H= 6, p = 0.01.

  
8) The cross species comparisons are a bit strained despite the general similarities across tasks. For instance, humans appear to receive a continuous tally of past reward within each game, which explains their lack of later exploration once they understand the basic task. But rats could forget this information and decide to re-explore the options, particularly in games with long horizons though reward volatility on short horizon games may provide a separate reason to explore.

We thank the reviewer for bringing up this critical point. We want to point out the following:

We agree that despite the matching underlying structure, there are many differences between the rat and human version of the task (reward history vs no history, points for humans and juice for rats, effortful spatial runs in rats vs effortless key presses in humans). However, our main interest is in how humans and rats change their exploration behavior across horizon conditions. This horizon comparison is done within species (the difference in the physical implementation of the task should not contribute to the horizon difference within species), and then we showed a qualitative difference between species that humans increase whereas rats decrease the threshold parameter in long horizon condition compared to short horizon condition. Given the horizon differences is calculated within species, the task differences should cancel out within each species.

The reviewer is right that rats could re-explore because of forgetting. For the same number of guided trials, rats are equally likely to forget in H = 1 and H = 6. We agree that reexploring is an important form of exploration (uncertainty increases as animals forget, and reexploring can be considered a form of directed exploration), but forgetting does not predict a difference in behavior across horizon conditions.

9) The authors suggest that rats may be performing the task to satisfice instead of optimize, like their human counterpart. This is related (p. 17) to the higher tendency for humans to explore than rats. This conclusion is partly based on the idea that rats must exert more effort and may be less willing to explore (a point also made earlier in the manuscript). But of course this specific data refers to first trial exploration. Rats were not less willing to explore on long horizon games. As indicated above, they tended to switch back and forth throughout the game (i.e., even when they had sampled both reward contingencies).

This is a really good point. We agree that the difference in effort can not account for the fact that rats were willing to switch in later trials in long horizon games. This constant switching in later trials may indeed reflect random exploration. We agree it’s not accurate to say that “more effort” leads to “being less willing to explore”. In the modified manuscript, we emphasized that “more effort” relates more to “not optimize” rather than “not explore”. It changes the relative utility/effort balance of the options, so that it’s not worth risking getting a 1 drop (to optimize the check if the unguided reward is a 5) if the guided reward is 4 drops for rats. This deliberate way of exploration is directed exploration rather than random exploration. “Effort” might influence directed exploration more than random exploration. To properly test the effect of efforts on exploration, future experiments could potential run identical tasks in long/short distance (or maze vs boxes), we would predict that rats in an effortful setup will be less willing to engage in directed exploration than rats in an effortless setup.

10) The greater preference for high reward option and lower level of switching in the free choice vs. guided choice is interesting but one account not considered is that rats some feeder/spatial preferences that bias them on these free choice first trials that continuous to bias their performance to the same degree within each game. This make sense generally and also explains why the effect of free vs. guided choice is so stable across variables like guided reward size and horizon. This could be a long-term feeder bias or perhaps something more dynamic (e.g., like a preference for whichever feeder has been paying off better in recent sessions).

We thank the reviewer for raising this critical and insightful point. In a simplified way of attempting to account for the influence of short-term/long-term feeder bias, we calculated two measures. We first computed the reward from last game(most recent reward of the current feeder from a previous game within session) to quantify short-term feeder bias, and computed the average reward from last session to quantify long-term feeder bias.



We first plot p(explore) as a function of both (NaN means that the rat didn’t choose the guided feeder in the previous game) and (LS values are binned). ANOVA analysis showed that both LG (p < 0.001) and LS (p = 0.02) have significant influence on p(explore). These showed that rats do have feeder biases. (Humans do not.)

As a result, we repeated all the model-based analysis by including these two additional parameters in the model to account for feeder biases. Specifically, we have

Here, in addition to the current reward, decision threshold, and spatial bias, we added two new terms, the first LG term quantifying the influence of feeder bias from last game, and the second LS term quantifying the influence of feeder bias from last session. Parameter recovery shows that our model estimates the upper bound of the feeder bias coefficients (Fig S1). Through model fitting, we confirm and acknowledge that rats are influenced by both short-term and long-term feeder bias. LG coefficient is significantly larger in H = 6 than H = 1 condition, showing that short term feeder bias (from last game) has a significantly bigger influence on H = 6 games (p < 0.001). This is likely due to that rats spend more trials at H = 6 feeders within a session. There are no differences in long term feeder bias (from last session) between horizon conditions (p = 0.48).



Next, we confirm that after accounting for feeder biases, the model-based results in the paper still hold, e.g., we still see reliable differences in threshold between horizon conditions (All the figures are reproduced using this extended model) in Experiment 2. In particular, we still observe the difference in the threshold parameter between self-guided vs cue-guided trials.



Despite there exists feeder biases, our model suggests that the large difference in thresholds between self-guided vs cue-guided conditions is still present after accounting for feeder biases.

11) On a related note, a spatial bias parameter was computed in the model fitting but was not discussed.

The results of spatial bias parameter are added to the supplementary. The spatial bias is centered at 0 in all conditions in Experiment 1.



But we did observe a left side bias when rats were guided only once (nG = 0 and 1) in Experiment 2.

Chart, histogram

Description automatically generated

This reflects some additional biases that rats have. The bias does not change significantly with horizon (p > 0.05).   
Minor issues:  
12) P. 10 - statement about boredom or motor error seems to refer to residual responding at last trial but worded as if about the reason for the decrease in switching.

We thank the reviewer for pointing this out. We have rephrased this in P.10.

13) P. 11 - it says "3 or 4 drops for humans"

We have rephrased this in P.11