

## Response to Reviews

Reviewer 1:

1. This manuscript presents an empirical study and a computational investigation of the effects of object saliency on preschool-aged children's exploration patterns in a simplified 4-armed bandit task. The work is motivated from a broader literature on the developing prefrontal context and its role in guiding exploratory decision making, raising the hypothesis that children's ability to engage in systematic exploration could be explained by "different mechanisms": namely distributed attention that promotes broad information gathering. The experimenters tested their hypothesis by systematically manipulating the salience of a visual cue linked to differing reward outcomes in three conditions (Baseline - no salience; Congruent - salient object is high-reward object; Conflict - salient object is low-reward object). They find that children in the baseline condition explore "systematically", whereas children in the salient conditions do not. Specifically, however, children's exploratory responses in the Conflict condition approach random exploration, whereas children's responding in the Congruent condition show fast learning of the high-reward location and probability matching to these rewards. From these results, the authors suggest their claim is supported - that distributed attention is thus responsible for young children's broad exploratory search.

There is much to like about this paper. First, and most importantly, these questions are timely and deeply about core mechanisms in cognition. There is a large and growing literature on children's "active learning" which can stand to be tremendously informed by evidence for executive function and attention, specifically, in development. Furthermore, the use of modeling really helps to clarify the distinctions (as found in differing parameterizations) between conditions; I commend the authors on clearly articulating these models (and especially impressive to concisely explain the models in a short report format) The figures were particularly appreciated.

We appreciate these comments.

2. There are some big claims here for a brief report, and it's worth taking a closer look at the data for those claims. Most of my concerns stem from the claims drawn from this data, given potential "confounds" in the methodological approach (given the argument about PFC). One critical "high level" argument the authors present is that this evidence demonstrates that "attention drives exploratory behavior in early development", with the implication that finding evidence for this explains why one observes systematic exploration in childhood, despite a developing PFC. There are some strange logical jumps here, primarily with the authors use of the term "systematic exploration" to motivate their experiment. First, it's worth stressing that the Competition condition DOES tax the PFC as it involves inhibition ('avoid the salient cue') as well as finding and tracking the high

reward location, (not the salient cue). (Note that just because a PFC is developing, doesn't mean it is not critically being used.) This taxation appears to lead to broad, albeit random(-ish), search. But it's worth noting that children seemed able to avoid the trap of always choosing the salient cue in this condition (which I suspect the authors were originally hoping to find given the attention story). So attention is focused on an item, but children in this condition manage to not get trapped by it and still managed to search items broadly. In a sense, this is evidence in conflict with the authors primary claim, but because of the slightly odd definition of "systematic search" they are able to argue that random search (though it is broad) is not systematic.

There are a number of important points here, and to address these points we have substantially revised both the Introduction (pg. 4-5) and Discussion (pg. 17-18). It may indeed be the case that the Competition condition is more demanding of PFC than the other conditions. The previous version of the manuscript perhaps focused too much on contrasting PFC controlled processes with attention related processes. Since the developmental status of PFC at this age and, even more critically, its role in producing choices in children is not well understood, we have reduced the manuscript's focus on immaturity of PFC. Instead the more critical idea is that immaturity in attentional control plays a large role in producing children's choices. But this does not mean that children will simply choose the thing that captures their attention. The current version of the manuscript better explains these ideas and the important theoretical issues at stake.

3. So then what does systematic mean? Taking a closer look at "systematic exploration" reveals that children are not engaging in STRATEGIC exploration - indeed the children in the Baseline condition are doing something quite strange - despite only 4 locations and 100 trials, with consistent reward behind each image, children seem unable to learn (even by the 80th trial/last epoch!!) the location of the high reward value.

We agree that it is important to differentiate children's choice behavior from adult-like strategic or directed exploration. We use "systematic exploration" to refer to non-random (and non-exploitive) choice patterns, but we do not mean to imply that children's exploration is strategic. Our hypothesis is that immature attention control (and other mechanisms) produce behavior that samples the environment in a non-random way, but that children are not engaging in this exploration in a strategic manner. We've adjusted the text in the Introduction to make this distinction clearer (pg. 4-5), and clarify throughout the manuscript that by "systematic" we mean non-random.

We agree that children are doing something rather unexpected, but do not believe it is that they do not learn. In fact, it has been reported (<https://psyarxiv.com/72sfx/>) that almost all children knew which option was the highest at the end of an experiment with similar design, regardless of

what type of strategy they employed or how often they chose that option in the last block of the experiment. Plate et al. 2018 report an analogous finding, wherein despite children accurately indicating the best option following a probabilistic learning task, they were much less likely than adults to maximize their choices toward that option. We've added discussion of this point to the manuscript (pg. 17-18).

4. Or, perhaps, they are unwilling to choose that reward in favor of following this repetitive (probably clockwise or counterclockwise) search behavior. (What do these children think the goal of the task is?)

The instructions emphasize to children that they should try to get as many points (virtual candy) as they can, and that the more they get the more stickers they will earn. Most children seem to understand this and appear motivated to reach the benchmarks that indicate that they earned a sticker. Though they seem to understand the goal of the task, it is a critically important idea that children's and adults' decisions may be motivated by different goals. Children may be more motivated by learning than by performance. We've added some discussion of this to the General Discussion (pg. 18).

5. This is quite strange behavior, and we would be shocked to see adults behaving this way, over, say quickly learning and choosing the high reward value. But this point about what adults might do is important to the authors' logical claims. The implication that we can explain children's systematic exploration with attentional mechanisms implies that adults (who have fully developed PFC) should also show "systematic exploration" because they have another route to this important behavior (namely a developed PFC). But, but I bet dollars to donuts that adults wouldn't. Instead, they would look like the children in the Confirmation group (where attention is influenced, but where children quickly learned the distribution and reasonably began to probability match to the expected rewards. The authors classify the Confirmation group as non-systematic exploration (based on their model) - but it seems odd to put this group that quickly honed in on the task goals and learned as non-systematic as the same general classification as a group that got conflicting salience/cue information and struggled with random exploration.

So this all raises the question - what does "systematic" search really mean in this context and what would the authors predict adult behavior would look like? The logical extension of the argument is that adults (who have developed PFC and don't need to depend on diffuse attention) would also show this "systematic search". We don't know if this is the case because adults aren't tested in a Baseline condition, but there is strong reason to believe it would not turn out this way (see Plate work again here). The claims are muddled in an attempt to shoe-horn this experiment into the broad attention theoretical packaging.

We agree that it is quite unlikely that adults would exhibit the type of systematic behavior that children exhibit in this task. Our hypothesis is not that the PFC results in that type of behavior, but that PFC-controlled processes are necessary for the type of systematic or directed exploration that adults engage in—directing exploration toward parts of the environment with greater uncertainty. There is very little uncertainty in our task, and so adults should quickly learn that only very little exploration is needed. Based on that, we predicted that they would exploit the highest reward option and show only small effects of the saliency manipulation. The revision includes a new sample of adults, and while there are effects of saliency, adults maximized reward in all conditions, with very little influence of systematic exploration (see Figure 4, pg. 16).

Children are doing something quite different, which suggests little influence of these PFC-controlled processes, particularly since their behavior is not particularly effective at achieving their goals. Children's behavior in the Baseline condition is characterized by systematic patterns of switching, but we do not mean to imply that this is necessarily good or effective (in fact it leads to poor performance in this task)—and while their behavior differs in other important ways, both the Congruent and Competition condition show very little of these patterns that strongly characterize children in the Baseline condition.

We've adjusted the wording in the Introduction and Discussion to better explain what we believe children are doing, what we mean by "systematic", how it differs from what adults do (pg. 4-5). Additionally, a sample of adults was collected and analyzed in comparison to children, and our predictions for both groups is laid out in the introduction (pg. 5-6).

6. Overall, what the authors have is a lovely demonstration that when salience cues are aligned, children quickly learn reward distributions and probability match to those rewards. When those cues are in conflict, it taxes the system and children resort to a random search response. Under baseline conditions, children appear to miss the goal of the task (to maximize reward) or at least favor continued exploration, involving a routine one-after-the-next switching pattern. These are fine results (and convergent with Rista Plat's recent paper showing developmental change in search-to-maximization behavior in a pseudo k-arm bandit task); furthermore, the modeling provides a nice peek into their interpretation. I simply don't feel that the high-level "dressing" makes sense. Unfortunately, without this dressing, it also becomes a question of whether these results are "big picture" enough to fit into Cognition's already high bar.

We've adjusted the manuscript in a number of places, particularly Introduction and Discussion to achieve a more inclusive and nuanced treatment of the issues at stake. The inclusion of a sample of adults additionally helps to more

clearly define the developmental nature of these effects and emphasize the potentially important implications of these results. We believe the study remains an important step in better understanding these crucial processes and their role in cognitive development, making it relevant to a wide audience of cognitive scientists and a good fit for *Cognition*.

Minor notes:

1. It would be great to see the best fitting Beta parameters graphed out like the Phi Figure 4.

We've added a figure with graphs of the best-fitting Beta parameters.

2. Page 4: Typo in this sentence "Distributed attention early in life children may be a sacrifice..."

Thanks. The typo has been corrected.

3. Missing lit references:  
Plate, R. C., Fulvio, J. M., Shutts, K., Green, C. S., & Pollak, S. D. (2018). Probability Learning: Changes in Behavior Across Time and Development. *Child development*, 89(1), 205-218.

This reference is added to the revision.

4. See Gopnik's recent papers making a similar argument about distributed attention and search:  
The Philosophical Baby: What Children's Minds Tell Us About Truth, Love, and the Meaning of Life, by Alison Gopnik. *Teaching Philosophy*, 37(1), 118-122. (Chapters on "Attention Spotlight/Lantern")

Gopnik, A. (2010). How babies think. *Scientific American*, 303(1), 76-81.

A reference to Gopnik's recent work has been added.

Reviewer 2.

1. This is an interesting and well-written report discussing the results of an elegant experiment (confirmed by modeling of behavioral responses) the purpose of which was to examine whether attentional mechanisms are causally related to the tendency for systematic exploration in young children. The findings support the conclusion that when attention is exogenously captured through salient stimuli in a choice task, systematic exploration decreases. This effect is not simply due to saliency, as salient stimuli were only chosen when they were compatible with the highest reward.

We appreciate this comment.

2. Although it makes sense that the tendency for distributed attention in young children supports exploratory choice behavior, it would be important to expand on this relationship a little more in the introduction, especially with regards to systematicity. This relationship is currently stated, but not necessarily clearly supported by past literature or other argumentation. Perhaps a little more can be added on the Blanco & Sloutsky paper under review.

We've expanded sections of the Introduction and Discussion to better explain how children's distributed attentional pattern relates to exploration, and how specific attentional mechanisms could support systematicity in exploratory behavior, including further description of the previous studies (pg. 4, 5 and 17).

3. In the description of the current study on p. 5 it is important to state clearly the predictions for each of the 3 conditions (Baseline, Congruent, and Competition).

We've expanded this section to clearly describe predictions for each of the three conditions (pg. 5-6).

4. The relationship between attention maturation and PFC development is not sufficiently discussed neither in the introduction nor in the discussion. It would be important to situate these findings within neural models of attention and cognitive control, some of which may be aligned with the present predictions (e.g., the Matched Filter Hypothesis for Cognitive control, Neuropsychologia, 62, 2014). In some sense the results would appear paradoxical, but they are not—bottom-up attentional capture leads to systematic exploitation. However, which neural mechanisms support this behavior in the context of an underdeveloped PFC? How is this process different than the PFC-mediated top-down attentional control?

The manuscript has been updated to further discuss these issues. We especially appreciate the reference to Chrysikou, Weber, and Thompson-Schill's paper which is extremely relevant and overall consistent with our

findings and hypothesis. We've added discussion of this idea to the Introduction and Discussion (pg. 3, 4, and 17-18).

5. It would be helpful if the order of the conditions in the text and figures match (see Figure 1).

Thanks for the suggestion. The text has been updated in several places to follow the same order as in the figures.

Reviewer 3:

1. p. 3, not merely irrelevant stimuli that need to be filtered out, but often competing stimuli, as in the present experiment.

The text has been updated to reflect this point (pg. 3).

2. p. 4, Although immature relative to adults, PFC is far from absent in a nearly 5-year-old child (the mean age here).

This is good point. The manuscript has been updated to focus more on the cognitive processes supporting systematic exploration (i.e. cognitive control) in adults, how immaturities in them may contribute to children's choices and attention allocation, and to more accurately reflect the developing state of these processes and PFC at this age (pg. 4).

3. Use past tense throughout the ms.

The manuscript has been updated to consistently use past test.

4. p. 5, of course salience will influence attention allocation. What is developmental about this study? Only one age group is studied, and the age range is unclear because it is not reported. What would be the developmental hypothesis on this task?

We have now included a sample of adults in each condition and compare their behavior to that of young children. Additionally, we've added discussion of the developmental hypothesis and predictions for each age group (pg. 5-6). The age range for children is also now reported.

5. p. 5, were the three conditions equivalent on age and sex distribution?

Yes, children were equivalent across the conditions in terms of age and gender. We've added text noting this with the appropriate statistics (pg. 6).

6. p. 7, how well did the participants tolerate 100 trials? It is a lengthy task.

Children tolerate the task well. In fact, most are highly engaged and motivated by this task. Each trial lasts only a few seconds, and the entire experiment takes about 10-15 minutes to complete. We've added text to clarify this point (pg. 8).

7. pp. 7-8, the data show children learned to select the salient/rewarding stimulus and to avoid the salient/punishing stimulus. Presumably several nonhuman species would show a similar pattern. Why is this surprising? What novel information does it contribute?

It's true that the described possibility might not be surprising, but this is not what our study found. Children did not avoid the salient stimulus when it was low in value. We've added text to emphasize this result and why it is surprising in several places (pg. 9, 10, and 17).

8. p. 13, the histograms suggest a bimodal pattern of staying and switching in the baseline condition (i.e., "exploration"), a somewhat biased but still bimodal pattern in the competition condition, and a fully biased pattern to stay with the salient option in the congruent condition. What if the image did not change every trial in the experimental conditions but was still colored vs boring? This condition might help disentangle the effects of salience and reward learning.

This is an interesting suggestion for a future study. In the current study we were leveraging saliency with multiple factors (color and novelty) to maximize the effects, but it could be that these factors influence choices in different ways, and it would be important to disentangle them in the future.

9. This experiment is confounding attentional mechanisms with reward and motivation.

The goal of the current design was to disentangle the effects of saliency from its interactions with reward by including both the Congruent and Competition conditions, in that effects that were consistent between these two conditions (but different from Baseline) could be attributed to salience. We believe that the design achieves this goal. But, the interactions of reward and motivation with attentional mechanisms are undoubtedly complex (and only beginning to be understood in adults) and will need further work to disentangle. We discuss this important point in the Discussion (pg. 17-18).