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Abstract: Exploration is critical for discovering how the world works. Exploration should be particularly valuable for young children, who have little knowledge about the world. Theories of decision-making describe systematic exploration as being primarily driven by top-down cognitive control, which is immature in young children. Recent research suggests that a type of systematic exploration predominates in young children's choices, despite immature control, suggesting that it may be driven by different mechanisms. We hypothesize that young children's tendency to distribute attention widely promotes elevated exploration, and that interrupting distributed attention allocation through bottom-up attentional capture would also disrupt systematic exploration. We test this hypothesis by manipulating saliency of the options in a simple choice task. Saliency disrupted systematic exploration, thus indicating that attentional mechanisms may drive children's systematic exploratory behavior. We suggest that both may be part of a larger tendency toward broad information gathering in young children.

Suggested Reviewers:

Department of Psychology

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September 16, 2019

Professor Ori Friedman

Associate Editor

Cognition

Dear Professor Friedman:

Thank you for considering our manuscript entitled *Attentional mechanisms drive systematic exploration in young children* (manuscript number: COGNIT-D-18-00574), and for inviting us to revise and resubmit it. The reviewers offered a number of thoughtful comments and suggestions. In light of those comments and suggestions, we have made substantial improvements to our manuscript. This includes collecting new data from a sample of 108 adults and comparing them to the children's data included in the manuscript. In addition to these new data and analyses, improvements have been made to the Introduction and Discussion to achieve a broader and more nuanced treatment of the issues at stake, and to better situate the study's conceptual motivation and theoretical implications. We believe that all of these changes help to highlight the significance and novelty of our findings, and that our study constitutes an important step in better understanding the critical processes underlying decision-making and their role in cognitive development, making it of interest to a wide audience of cognitive scientists and a good fit for publication in *Cognition*. We hope that you will find this version acceptable for publication, and we look forward to hearing from you.

Sincerely,

Vladimir Sloutsky

Professor of Psychology

Nathaniel Blanco, Ph.D.

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 it's 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", where-as children in the salient conditions do not. Specifically, however, children's exploratory responses in the Conflict condition approach random exploration, where-as 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 begain 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. (Chapers 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).

Attentional mechanisms drive systematic exploration in young children

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Running Head: Exploration and Attention

Word Count: 2999

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Abstract

Exploration is critical for discovering how the world works. Exploration should be particularly valuable for young children, who have little knowledge about the world. Theories of decision-making describe systematic exploration as being primarily driven by top-down cognitive control, which is immature in young children. Recent research suggests that a type of systematic exploration predominates in young children's choices, despite immature control, suggesting that it may be driven by different mechanisms. We hypothesize that young children's tendency to distribute attention widely promotes elevated exploration, and that interrupting distributed attention allocation through bottom-up attentional capture would also disrupt systematic exploration. We test this hypothesis by manipulating saliency of the options in a simple choice task. Saliency disrupted systematic exploration, thus indicating that attentional mechanisms may drive children's systematic exploratory behavior. We suggest that both may be part of a larger tendency toward broad information gathering in young children.

Keywords: cognitive development; exploration; decision-making; attention

Attentional mechanisms drive systematic exploration in young children

Cognition changes dramatically in the course of development. Many of these changes stem from developmental changes in allocation and control of attention. Adults are adept at controlling their attention: depending on their goals, they can distribute it broadly or focus selectively on a small subset of stimuli (e.g., Chong & Treisman, 2005). When only some of the available information is relevant, adults tend to selectively focus on that information and ignore the rest (Rehder & Hoffman, 2005; Blair, Watson & Meier, 2009).

In contrast, young children tend to distribute their attention broadly, regardless of task demands, often processing both task-relevant and task-irrelevant information (Deng & Sloutsky, 2015, 2016; Plebanek & Sloutsky, 2017; Smith & Kemler, 1977). This tendency likely stems from immaturities of executive attention (Posner & Rothbart, 2007), resulting in difficulty attending selectively and filtering out less relevant input.

While such immaturities of executive attention may be limiting for learning in academic settings, it is possible that they can be adaptive (Chrysikou, Weber, & Thompson-Schill, 2013; Gopnik, 2010). For example, distributing attention can result in superior performance of children over adults in situations where one has to use information that was previously irrelevant (Plebanek & Sloutsky, 2017; Blanco & Sloutsky, 2019).

Depending on the context, either selective or distributed attention can be advantageous. Selective attention is superior when one is confident that a fraction of the available information is sufficient for their goals. Distributed attention is advantageous when there is more uncertainty about what is important. Therefore, distributing attention may be particularly adaptive early in development, since young children have little knowledge of the world. By facilitating broad information gathering, distributed attention helps reduce uncertainty and build up a rich base of knowledge. Distributed attention early in life may represent a sacrifice of immediate performance in exchange for information. These ideas are consistent with the *matched filter hypothesis* of cognitive control (Chrysikou, Weber, & Thompson-Schill, 2013), which proposes that less cognitive control may lead to more errors but better learning over time.

In other words, distributing attention may facilitate exploration. Recent research suggests that there is a tight link between attention allocation and choices (Konovalov & Krajbich, 2016; Smith & Krajbich, 2018), and perhaps wider attention allocation also promotes wider distribution in action selection. There are recent reports indicating that children's choices are, indeed, highly exploratory (Blanco & Sloutsky, 2019 *PsyArXiv*; Sumner et al., 2019 *PsyArXiv*; Schulz, Wu, Ruggeri, & Meder, 2019 *BioRxiv*). Interestingly, children's exploration also appears non-random. This is surprising because decision-making research critically distinguishes systematic from random exploration (Badre, Doll, Long, & Frank, 2012; Daw, O'Doherty, Dayan, Seymour, & Dolan, 2006; Knox, Otto, Stone, & Love, 2012; Somerville, et al., 2017), and converging evidence suggests a crucial role of executive control processes mediated by prefrontal cortex (PFC) in systematic exploration (Badre, Doll, Long, & Frank, 2012; Blanco et al., 2015; Otto, Knox, Markman, & Love, 2014). Given the protracted development of cognitive control and PFC (Bunge et al., 2002; Casey, Giedd, & Thomas, 2000; Sowell, et al. 1999), current theories imply that young children's exploration should be largely unsystematic (Somerville et al., 2017). However, recent evidence suggests young children perform systematic exploration, although they may not explore *strategically* the way that adults do (Blanco & Sloutsky, 2019 *PsyArXiv*). Specifically, 4-year-olds switched between options at extremely heightened rates, and switched more often to less recently selected options, even when this systematic sampling provided very little information.

These findings raise the possibility that young children's systematic (i.e., *non-random*) exploration is driven by different mechanisms than adults' *strategic* exploration. We hypothesize that children's exploratory behavior is tied intricately to their immature attention allocation.

The Current Study

The goal of the study was to test this idea by modulating attention allocation by manipulating salience of a cue linked to a reward. We presented children and adults with a simple decision-making task under three conditions to examine the interplay of attention and choice patterns across development. The conditions differed in terms of the perceptual saliency of stimuli marking the choice options: a *Baseline* condition where all options were of equal salience, a *Competition* condition where a salient option was mapped to the lowest reward (putting reward-seeking and salience in competition), and a *Congruent* condition where the salient option was mapped to the highest reward.

Our hypothesis was that children's tendency to distribute attention promotes distributing choices across available options. In the same way that attention shifts over time and is less likely to return to recently focused items, less recently chosen or attended options may become increasingly appealing over time. This tendency, therefore, may enable systematic (i.e., non-random) exploration. In adults, the decision process is instead associated with selective attention to highly rewarding options.

We predicted that most children in the Baseline condition would engage in systematic exploration (Blanco & Sloutsky, 2019 *PsyArXiv*), with few children exploiting the best option. If altering children's attentional pattern through bottom-up capture of attention also affects exploratory behavior, we can infer a strong connection between attention and exploratory behavior early in development. In contrast, if attention is not a causal factor in children's exploratory behavior, manipulating attention should lead to little or no change in their choices. Therefore, our main prediction was that this systematic pattern would be disrupted in both the Congruent and Competition conditions.

The exact role of saliency on children's choices could manifest in several ways. One possibility was that children's choices would be driven largely by saliency, leading to selecting the most salient option regardless of its reward value. Another hypothesis was that saliency would act as a learning cue, leading to faster prioritization of the salient option in the Congruent condition and avoidance of it in the Competition condition. In contrast, small to no effects of saliency were expected in adults, who were expected to maximize reward, exploiting the high-value option in all conditions.

Method

Participants

A total of 110 4-to-5-year-olds (mean age=57 months; range=48-69 months; 58 girls, 52 boys) participated: 36 in the Baseline, 37 in the Competition, and 37 in the Congruent conditions. Children did not differ by condition in terms of age, $F(2,107)=2.01$, $p=0.139$, $\eta^2=0.04$, or gender, $X^2(2;N=110)=2.01$, $p=0.367$. 108 adults also participated (mean age=19 years; range=18-29 years; 60 women, 45 men, 3 other responses): 37 in the Baseline, 34 in the Competition, and 37 in the Congruent conditions. Child participants were recruited from preschools and childcare centers in the Columbus, Ohio area. Adults were undergraduate students participating for course credit.

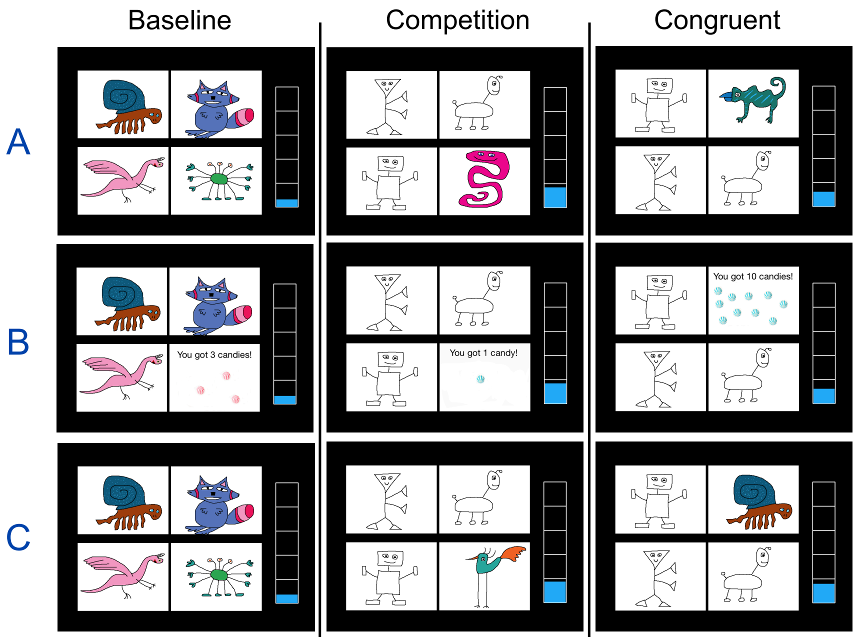

Figure 1: Trial structure. (A) After each choice, (B) the reward earned for the choice was presented for 3 s, (C) then the next trial began. In the Congruent and Competition conditions one option was represented by a colorful image that changed on every trial, while the other three were represented by lower salience images that remained stable across trials. In the Baseline condition, all four options were represented by stable images of equal salience.

Procedure

Participants completed a simplified *n*-armed bandit task, framed as a computer game in which participants collected virtual candy from alien creatures (Figure 1). The goal was to earn as much candy as possible. On each of 100 trials, participants chose one of four creatures and received virtual candy according to their choice. Each creature gave a fixed reward throughout the experiment: 1, 2, 3, and 10 candies, respectively. The locations of these rewards were fixed across the experiment but were randomly determined for each participant. Following the choice, the resulting reward was displayed for 3 s, and a meter tracking the total accumulated candy was updated. Children earned stickers for every 180 candies earned, with benchmarks on the meter indicating these goals. The experiment took 10-15 minutes to complete.

Participants were assigned to one of three conditions. In the Baseline condition, all creatures were approximately equally salient, whereas in the Congruent and Competition conditions, salience was unequal. Specifically, three of the creatures were black-and-white stick figures, whereas one was colorful and perceptually rich. Additionally, on each trial the salient image was a different novel creature (Figure 1C). Fifty unique images were used for the salient option, each appearing twice during the experiment. In the Competition condition, the salient option was mapped to the lowest reward (1 candy), whereas in the Congruent condition, the salient option was mapped to the highest reward (10 candies).

Results

Choice proportions

Participants' choices over the course of the experiment are presented in Figure 2. To assess the effect of saliency on performance, we analyzed the proportion of trials that the highest-valued option was chosen. A 3x2 (age group by condition) ANOVA revealed a main effect of age group, $F(1,212)=391.93$, $p<0.001$, partial-$\eta^2=0.65$, a main effect of condition, $F(2,212)=20.89$, $p<0.001$, partial-$\eta^2=0.16$, and a significant interaction, $F(2,212)=6.17$, $p=0.002$, partial-$\eta^2=0.06$.

ANOVA's within each age group revealed significant effects of condition for each group [children: $F(2,107)=15.40$, $p<0.001$, $\eta^2=0.22$; adults: $F(2,105)=10.68$, $p<0.001$, $\eta^2=0.17$]. Specifically, children chose the highest-value option more often in the Congruent condition ($M=0.53$) compared to the Baseline ($M=0.28$), $t(71)=4.40$, $p<0.001$, $d=1.03$, and Competition conditions ($M=0.30$), $t(72)=3.93$, $p<0.001$, $d=0.91$. The Competition condition was not different from Baseline, $t(71)=0.57$, $p=0.569$, $d=0.13$. The effect was different for adults: participants in the Competition condition ($M=0.77$) chose the best option less than both the Congruent ($M=0.94$), $t(69)=3.86$, $p<0.001$, $d=0.92$, and Baseline conditions ($M=0.91$), $t(69)=2.94$, $p=0.004$, $d=0.70$. The Congruent and Baseline conditions were not different from each other for adults, $t(72)=1.50$, $p=0.137$, $d=0.35$.

The proportion of trials in which the lowest-valued option was chosen was analyzed to test the effect of salience in the Competition condition. A 3x2 (age by condition) ANOVA revealed a main effect of age group, $F(1,212)=55.84$, $p<0.001$, partial-$\eta^2=0.21$, a main effect of condition, $F(2,212)=13.68$, $p<0.001$, partial-$\eta^2=0.11$, and a significant interaction, $F(2,212)=3.58$, $p=0.030$, partial-$\eta^2=0.03$. There were also effects of condition within each group, [children: $F(2,107)=5.24$, $p=0.006$, $\eta^2=0.09$; adults: $F(2,105)=10.88$, $p<0.001$, $\eta^2=0.17$]. For children, pairwise tests revealed only that participants in the Congruent condition ($M=0.16$) chose the lowest option less than both the Baseline ($M=0.23$), $t(71)=3.22$, $p=0.002$, $d=0.75$, and Competition conditions ($M=0.25$), $t(72)=2.60$, $p=0.011$, $d=0.60$. The Competition and Baseline conditions did not differ significantly, $t(71)=0.65$, $p=0.516$, $d=0.15$. For adults, participants in the Competition condition ($M=0.17$) chose the lowest-value option more often than both the Congruent ($M=0.02$), $t(69)=3.40$, $p=0.001$, $d=0.81$, and the Baseline conditions ($M=0.03$), $t(69)=3.23$, $p=0.002$, $d=0.77$. The Congruent and Baseline conditions were not different from each other, $t(72)=1.03$, $p=0.308$, $d=0.24$.

In summary, there was a straightforward effect of saliency in adults: in the Competition condition, the highest option was selected less frequently, and the low-valued option was selected more frequently, compared to the other conditions. The pattern of results in children is more complicated. Saliency facilitated choosing the highest option in the Congruent condition, but had no effect in the Competition condition: the salient option was selected neither more frequently (which would be expected if choices were purely salience-driven) nor less frequently (which would be expected if salience facilitated learning).

Switch proportions

To further examine effects of salience, we analyzed the proportion of trials that participants switched responses, choosing a different option than the previous trial, as an indicator of elevated exploration (Figure 3). In the Baseline condition, we expected children to switch often and systematically. While, because outcomes were stable, low levels of exploration would usually be expected, a previous study showed that children tended to switch extremely often (Blanco & Sloutsky, 2019 *PsyArXiv*)—consistent with highly elevated exploration. Systematicity in their switching was then established with subsequent computational modeling analyses. We, therefore, first analyze participants' switch responses, and we report modeling results in the next section.

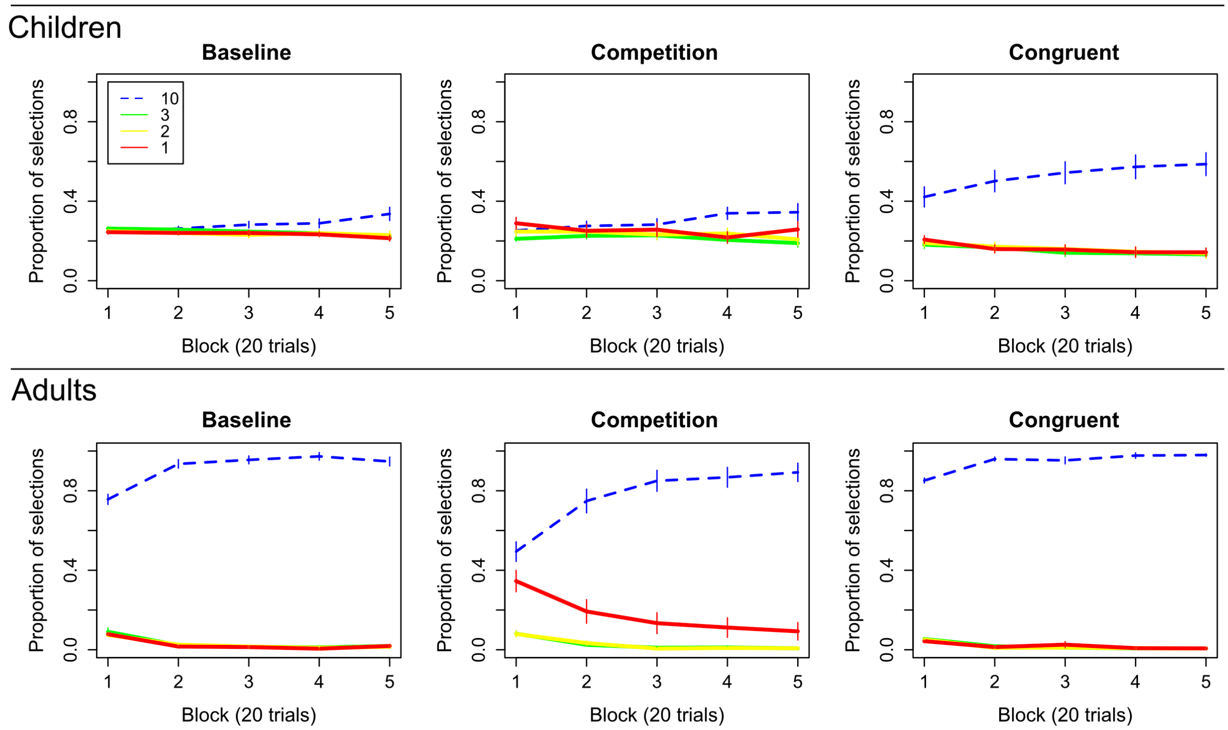

Figure 2: Choice proportions. The proportion of trials on which each option was chosen is presented for blocks of 20 trials. Children in the Congruent condition selected the highest-valued option more frequently than children in both the Baseline and Competition conditions. Interestingly, children in the Competition condition did not select the lowest-valued option (which was salient in that condition) more often than in the Baseline condition. This suggests that simple salience-seeking did not drive children's choices. Adults exploited the highest-value option in all conditions and selected the lowest option more often when it was salient (in the Competition condition). Error bars reflect standard errors of the mean.

A 3x2 (age by condition) ANOVA on switch proportions revealed a main effect of age group, $F(1,212)=577.83$, $p<0.001$, partial-$\eta^2=0.73$, a main effect of condition, $F(2,212)=17.86$, $p<0.001$, partial-$\eta^2=0.14$, and a significant interaction, $F(2,212)=12.50$, $p<0.001$, partial-$\eta^2=0.11$. For adults, switching was low overall ($M=0.117$), and there was no effect of condition, $F(2,105)=1.90$, $p=0.154$, $\eta^2=0.03$.

Importantly, children's switch proportions were affected by the saliency manipulation, indicated by an effect of condition, $F(2,107)=17.42$, $p<0.001$, $\eta^2=0.25$. Children in the Congruent ($M=0.56$), $t(71)=5.57$, $p<0.001$, $d=1.30$, and Competition conditions ($M=0.77$), $t(71)=3.22$, $p=0.002$, $d=0.75$, switched substantially less than Baseline ($M=0.91$). Additionally, children in the Competition condition switched more than those in the Congruent condition, $t(72)=3.04$, $p=0.003$, $d=0.71$. It is not surprising that switching was relatively low in the Congruent condition since children were exploiting the best option instead. But it is surprising that switching was relatively low in the Competition condition despite no increase in exploitation.

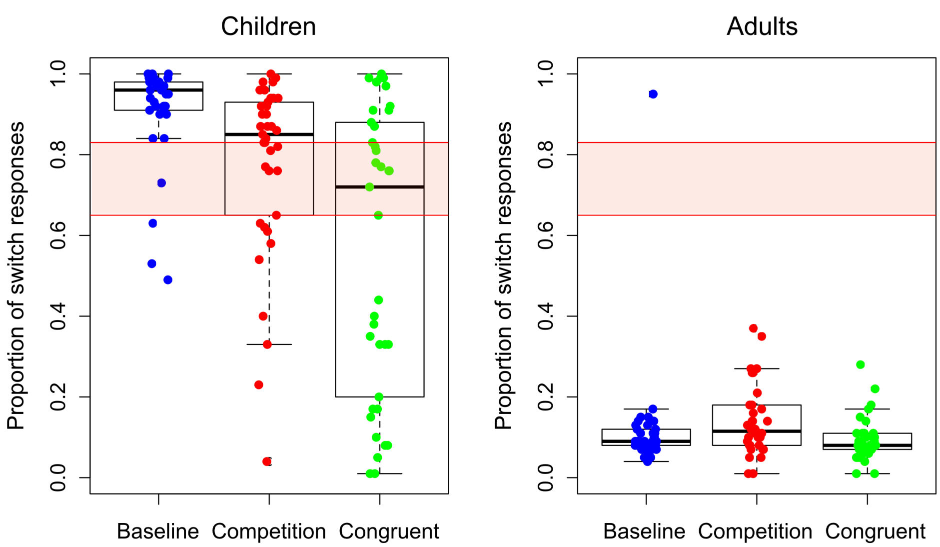

Figure 3: Response Switching. The proportion of trials on which participants made a switch response, choosing a different option than the previous trial, is presented. The pink shaded region represents 95% probability density of switch responses given random responding. Extreme switch proportions for children in the Baseline condition suggest elevated exploration levels. Children's switch proportions are less than the Baseline in both salience conditions. In contrast, adults rarely switch, instead exploiting the best option. Dots represent individual participants.

Computational Modeling

To examine the effects of the salience manipulation on systematic exploration, participants' choices were evaluated in relation to a Reinforcement Learning model (Sutton & Barto, 1998) that included both systematic and random exploration (Blanco & Sloutsky, 2019 *PsyArXiv*). The model used prediction errors to learn expected reward values for each option using the following equation:

$$V_{i,t+1} = V_{i,t} + \alpha\left(R_{i,t} - V_{i,t}\right)$$

where $V_{i,t}$ is the expected value of option i on trial t, $R_{i,t}$ is the reward on trial t earned for choosing option i, and α is the learning rate (a free parameter). It then made choices according to the following function:

$$P\left(a_{i,t}\right) = \frac{e^{\beta * [V_{i,t} * (1-\phi) + L_{i,t} * \phi]}}{\sum_{j=1}^{n} e^{\beta * [V_{j,t} * (1-\phi) + L_{j,t} * \phi]}}$$

where $P(a_{i,t})$ is the probability of choosing option i on trial t. $L_{i,t}$ is the lag term that simply encodes the number of trials since option i was last chosen. The weight parameter ϕ $(0 \leq \phi \leq 1)$ mediates the relative weights of expected values (i.e. exploitation) and lags (i.e. systematic exploration) in determining choices. Greater values of ϕ indicate greater influence of systematic exploration. When ϕ=0, the model chooses based only on expected value; when ϕ=1, it chooses only based on the lag. β is the inverse temperature parameter that controls random exploration. At β=0 choice probabilities become completely random (i.e. equal between all options). As β approaches infinity the model chooses the most favorable option (based on the weighted combination of value and lag described above) on every trial. β and ϕ were free parameters.

The best-fitting parameter values were compared across groups and conditions to determine the influences of reward, systematic exploration, and random exploration on participants choices (Figure 4). A 3x2 (age by condition) ANOVA on best-fitting ϕ found a main effect of age group, $F(1,212)=82.11$, $p<0.001$, partial-$\eta^2=0.28$, a main effect of condition, $F(2,212)=9.61$, $p<0.001$, partial-$\eta^2=0.08$, and a significant interaction, $F(2,212)=6.92$, $p=0.001$, partial-$\eta^2=0.06$. For adults there was no effect of condition, $F(2,105)=1.62$, $p=0.20$, $\eta^2=0.03$, whereas for children, there was an effect of condition, $F(2,107)=8.80$, $p<0.001$, $\eta^2=0.14$, such that ϕ was higher for the Baseline condition compared to both the Congruent, $t(71)=4.36$, $p<0.001$, $d=1.02$, and Competition conditions, $t(71)=2.47$, $p=0.016$, $d=0.58$. The Congruent and Competition conditions were not significantly different, $t(72)=1.56$, $p=0.123$, $d=0.36$. The high values of ϕ in the Baseline condition and substantially lower values in the other conditions suggest that the salience manipulation dramatically decreased systematic (non-random) exploration in in these conditions compared to Baseline.

A 3x2 (age by condition) ANOVA on best-fitting β (Figure 5) found no main effect of group, $F(1,212)=0.14$, $p=0.708$, partial-$\eta^2<0.001$, no effect of condition, $F(2,212)=1.57$, $p=0.211$, partial-$\eta^2=0.015$, and no interaction, $F(2,212)=0.38$, $p=0.688$, partial-$\eta^2=0.003$.

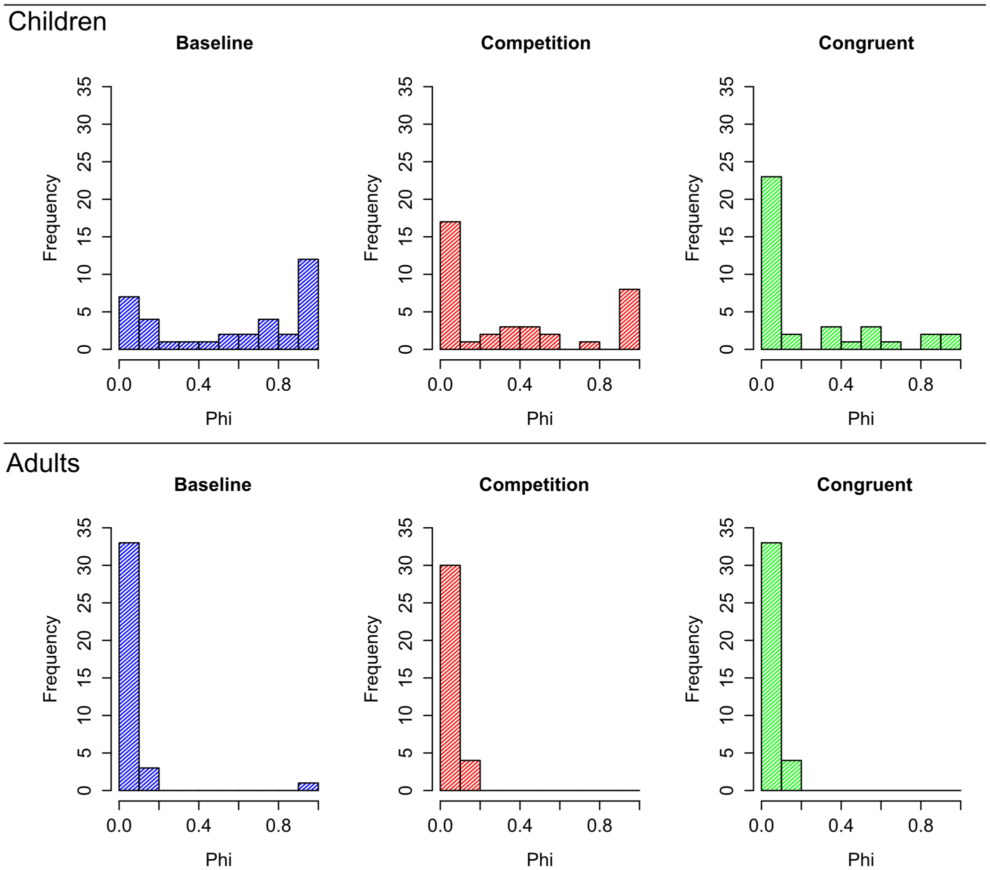

Figure 4: Best-fitting ϕ parameter. Histograms of the best-fitting ϕ parameter for each group are presented. Both salience conditions had a large proportion of children with very low values of ϕ, indicating little systematic exploration, while the Baseline condition had a larger proportion of participants with high values of ϕ, indicating higher levels of systematic exploration. Almost all adults had low ϕ, indicating their choices were largely driven by reward value.

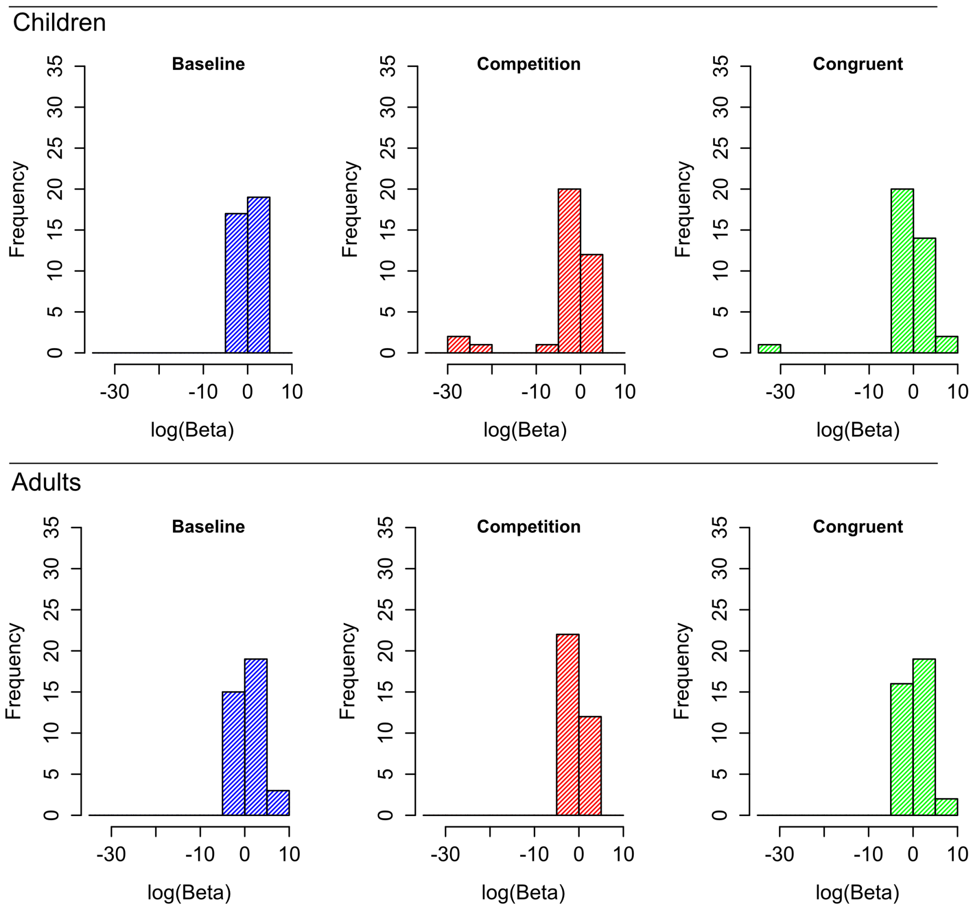

Figure 5: Best-fitting β parameter. Histograms of the log of best-fitting β (which controls the rate of random exploration) are presented. Log(β) is presented rather than raw values because large outliers make graphing the raw values difficult. There were no significant age or group effect on best-fitting β value.

Discussion

The goal of the current study was to examine the link between children's exploration and attention by manipulating attention and observing effects on their choice patterns. The results suggest that attentional manipulation (i.e., exogenously capturing attention through large differences in salience) decreased the level of systematic (non-random) exploration in young children compared to a Baseline condition—where they were systematic and highly exploratory.

Conversely, while adults showed effects of saliency on their choice proportions, they were highly exploitative in all conditions, with very little influence of saliency on systematic exploration (Figure 4).

Additionally, children's choices were not simply salience-driven; the effect of saliency was dependent on whether or not salience was congruent with reward value. When the salient option was valuable, children chose it more often than in the other conditions. But, when the salient option was low in value, it was not chosen more (or less) often than in the Baseline condition. It was also not selected less than the other options, suggesting that the results were not simply due to saliency facilitating learning.

These results suggest a complex influence of attention on young children's choices, and point to an integral role of children's immature attentional allocation in facilitating systematic exploration—in contrast to adults' tendency to both selectively attend and maximize reward. When salience is equivalent among the options, systematic exploration dominates, with less recently sampled options more likely to be selected. It may be that children's default attention allocation pattern enables systematic exploration through graded novelty preference (wherein novelty steadily increases over time as an option is not attended, becoming more likely to attract attention). Manipulating bottom-up attention disrupts this process by altering the relative saliency of the choice options, leading to a reduction in systematic choice patterns.

Attention and decision-making may be intricately linked in both children and adults (Konovalov & Krajbich, 2016; Smith & Krajbich, 2018), and developmental changes in attention may be an important factor in the development of decision-making. Children's increasing ability to attend selectively may coincide with an increase in maximizing their choices toward rewarding actions. Younger children's choices seem to be geared toward learning rather than maximizing reward, a tendency which may be directly linked low cognitive control (Chrysikou, Weber, & Thompson-Schill, 2013), and which is supported by several recent findings showing that, despite knowing the best option, children are less likely than adults to maximize their choices toward it (Plate et al. 2018; Blanco & Sloutsky, 2019 *PsyArXiv*).

Understanding the critical and complex interaction of attentional mechanisms and decision-making is an exciting area of future research and may be particularly important factor in understanding cognitive development.

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