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Corresponding Author: Dr. Nathaniel J. Blanco, Ph.D.

Corresponding Author's Institution: The Ohio State University

First Author: Nathaniel J. Blanco, Ph.D.

Order of Authors: Nathaniel J. Blanco, Ph.D.; Vladimir M Sloutsky, Ph.D.

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:

Research Data Related to this Submission

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April 30, 2020

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 some additional useful comments, including some intriguing alternative explanations of our results. In light of those comments we have made revisions to our manuscript. Most notably, we added a new section to the General Discussion "Unanswered questions and future directions" in which we consider some of the explanations and concerns of the reviewers and the importance of addressing them with future research. We also made revisions throughout the manuscript to clarify and emphasize the specific contribution our findings and their implications for understanding critical aspects of cognitive development. We hope that you will find this version acceptable for publication, and that you will find our revisions sufficient to make a decision yourself (without sending it back to the reviewers). We look forward to hearing from you.

Sincerely,

A handwritten signature in black ink, appearing to read "Nathaniel Blanco".

Nathaniel Blanco, Ph.D.

A handwritten signature in black ink, appearing to read "Vladimir Sloutsky".

Vladimir Sloutsky

Professor of Psychology

## Response to Reviews

### Editor's comments:

Also, please consider these two minor points:

-I don't know if it would be possible to convey the expected Phi value if participants always switched, but responded randomly besides this (e.g., after choosing A, randomly choose between B, C, or D). But if a Phi value is associated with this kind of strategy, expressing it might help readers better interpret the findings. (The more general point is that the extreme Phi and Beta values are clearly expressed, but it might help to have some indication of what at least one other value might imply).

Unfortunately, it is hard to associate a specific value of phi with this type of strategy since it would appear more like random responding, resulting in the model being best fit with a very low beta value, at which point phi becomes unidentifiable. To test whether this was the case, we ran simulations using this strategy and fit the model to the simulations. The model fit this strategy poorly (much worse than to participants' data), and the resulting phi values were highly variable, with the whole range of possible values (from close to 0 to close to 1) occurring across different simulations. We agree, however, that it would be useful to include what another value of phi might represent to facilitate readers' understanding of the model. We have noted in the text that a value of 0.5 represents approximately equal weighting of reward values and choice lag in producing responses.

As a side note, in a previous project with a task equivalent to the Baseline condition, we tried a model that encapsulates the random switching strategy that is described above and found that for almost all children it was a worse fit than the model that we use in the current work.

-For papers to be accepted at Cognition, the data need to be made publicly available (e.g., in a public repository like OSF). So it may save time later if you were to provide the link in the next version of the paper.

We have added the data to a repository on OSF (<https://osf.io/ph9kz/>) and have included a link in the manuscript.

### Reviewer #1:

My concern continues to be that I'm not sure this data actually speak to a deep attentional shift/disruption; it's still not entirely clear how the children are interpreting the task, and so I don't believe there needs to be a story about attention at all here (as much as I'm sympathetic to this account and also believe it to be a deeply interesting story). Specifically, consider that children just have a heuristic, that when a task is

about exploration/sampling, the job is to try each one in succession. This doesn't have to be because their attention is broader (indeed, you could have perfectly focused attention and still decide to follow a rule to sample in an order, such as clockwise around the quadrants.) The question is -- what happens when the task becomes less clear -- because there is suddenly one object (salient) that is not like the others. The children must then figure out why that object is different and how it is supposed to relate to the task. In the case when it is convergent with the reward, the inference is fairly apparent and young learners should quickly converge on maximizing the salient cue. When the cue is not the highest reward, the cue becomes confusing in that the purpose of the task may be less clear -- leading to more random (but not systematic) exploration. My point is simply that this explanation for the behavior does not depend on a claim of children having more distributed attention; and these results cannot thus be taken as evidence that a salient cue thus disrupts this broad attention.

The reviewer brings up an interesting alternative explanation. The reason that we doubt the likelihood of this specific alternative is that it suggests that young children are using an explicit rule. However, because such exploration decreases with age (in fact, we have yet unpublished data indicating that systematic exploration increases in infancy to about 3-years of age, and then decreases between ages of 3 and 7). Given these data, we should conclude that the rule use decreases with age, which appears highly unlikely. Additionally, this alternative requires three separate explanations to account for the results of the three conditions, whereas an attentional explanation can account for the levels of systematic exploration in all three conditions with a single mechanism. We have updated the Discussion (pg. 17) to better highlight this point. We agree, however, that since we did not measure attention directly, we cannot rule out the possibility that disrupting distributed attention is not the primary factor driving differences and between the Baseline condition and other conditions in children. In light of these concerns, we note this possibility in Discussion and the importance of directly measuring attention (e.g. with eye-tracking) in future studies (pg. 18).

Indeed, the adult data speak more strongly to the claim that the saliency "breaks" the broader attentional pattern, as adults over-select the wrong item in the conflict condition, suggesting it is the adults (and not the children) that have a hard time inhibiting the saliency. This is almost counter to the broader story the authors are making, but the fact that I could tell a just-so story either way leads me to be concerned that we cannot speak clearly to the broader, developmental-cognitive theory posited here to help motivate and interpret this study.

While it is true that both children and adults show effects of saliency on choice proportions, raw choice proportions alone cannot tell the full story because a variety of different strategies may lead to similar choice proportions. The computational modeling analyses of participants' choice pattern are critical to uncovering these differences in strategy. Children's overall strategy changes between conditions, whereas adults' does not. When saliency is manipulated, children show a reduction in response switching and an overall shift from

systematic toward more random exploration. This disruption of systematic exploration due to the saliency manipulation is informative and occurs only in children. So, while it may be possible to come up with a variety of different explanations based only on the choice proportions, the modeling analyses reveal important differences between adults and children that provide a clearer picture with important implications for developmental-cognitive theory.

In the revision we tried to better highlight the importance of the modeling analyses, the differences between conditions that they uncover, and the implications for cognitive development. We have made changes throughout the manuscript, notably on pages 6, 10, and 17.

More minor note:

On page 5, the authors note "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." The statement requires citation and even conflicts to some extent with recent work on attention and decision making (that more "attended to" items are more likely to be chosen in a singular decision; data from Krajbich & Rangel, 2011; modeling work from Callaway & Griffiths, 2019). It may strengthen the authors' argument to state why the less recently chosen/attended options become more appealing. Is this true for both children and adults? Intuitively it would feel correct for children, whose "meta-goal" within the game may be to learn about the world, such that appeal arises from opportunity for information gain.

We thank the reviewer for this observation and suggestion. We have expanded on this specific point in the Introduction (pg. 5) in order to clarify our hypothesis. The referenced work is consistent with our hypothesis, and in fact, work from Krajbich and colleagues was highly influential in motivating these ideas. The attentional mechanisms that the reviewer alludes to and those that we are referring to operate at different time-points in the decision process. It is true that within a single decision attended to items are more likely to be selected in adults, and this may also be true in young children (indeed, our hypothesis assumes that it is). But, after a choice is made (and the outcome for that choice observed) there may be little reason to continue to attend to the object and attention may shift. The way that it shifts is likely different between adults and children, wherein adults control attention to continue focusing it selectively on rewarding options, while children are more likely to shift to a new option. Attention would then influence choices in the way that is suggested by the referenced work. More specifically, we suggest that children's shift may be driven by something like graded novelty preference: the recently chosen option is no longer novel, but the unselected options have been increasing in novelty since last being chosen. We further describe and clarify this idea in the revision (pg. 5).

### **Reviewer #3:**

The authors have been highly responsive to the previous reviews. It is especially helpful to have the adult comparison group. The authors have clarified what is potentially novel about these results.

Their argument shares some similarities with the Hierarchical Competing Systems computational model of the effect of the number of "A" trials on A-not-B task performance in infants and toddlers (see Marcovitch & Zelazo, 2009), which might be worth mentioning in the introduction.

We thank the reviewer for pointing us toward this interesting work. We have added a brief discussion of this idea to the Introduction (pg. 5).

What is most surprising about the results to me is children's performance in the Baseline condition. Why don't they home in on the high value option and stick with it, like adults do?

We agree that children's behavior in the Baseline condition is extremely interesting, and that understanding could be important. We are very interested in this question. The current paper is a follow-up to our original study that reports this effect (Blanco & Sloutsky, 2019 *PsyArXiv*) and is one part of a larger line of ongoing research that attempts to better understand this behavior.

Three non-exclusive alternative interpretations of the results for the authors to reconsider:

Children had difficulty learning to maximize rewards in this task, as shown in the Baseline. Salience scaffolded learning in the Congruent condition, but it disrupted learning in the Competition condition, where they knew the salient cue was low in value, yet could not resist it occasionally. It is a straw man argument to suggest that 5-year-olds would be lured 100% by salience alone, even when it conflicts with reward value (again, PFC is not absent at this age). On this account, it is not that their choices were "geared toward learning rather than maximizing reward" (pp.17-18), but instead, they are learning HOW to maximize rewards in the face of distracting stimuli.

This is an intriguing idea, and it may be that case that one thing that children are learning is how to maximize rewards in the face of distracting stimuli. This possibility does not contradict our interpretation or results, though. But, there is little evidence to support this interpretation in the current data, since it would suggest that children should maximize reward when there are no distracting stimuli (as in the Baseline condition). Few children do so. Children in the Baseline condition systematically explored instead of maximizing reward. Furthermore, the current study cannot distinguish between not learning to maximize reward, and simply preferring not to, so it would be misleading to suggest that children had difficulty learning to maximize reward in this task.

Indeed, in our previous study (Blanco & Sloutsky, 2019 *PsyArXiv*) we found that most children knew what the best option was despite not choosing it more often than the other options. In addition, we cannot conclude that salience disrupted *learning* in the Competition condition, since choice proportions were equivalent to the Baseline condition. The main difference between the conditions is revealed by the modeling analyses which instead show a substantial disruption of *systematic exploration* in the Competition condition. While children's choices are likely generally geared toward learning, it is hard to say what, if anything, children were learning in the Competition condition given their largely random responding in that condition.

It could also be that children were less motivated than adults, insofar as the rewards were quite distant; they were symbolized by drawings, which symbolized the value of candy in text, which was translated into a meter tracker, which symbolized not candy, but stickers (how many?) for every 180 "candies" earned. Although adults would understand this, and might be quite motivated to do well even without the cover story of candies or stickers but merely "points," it is possible this was too abstract for children. The salient cue in the Congruent condition helped them just enough to perform better, despite them not really understanding the symbolic goal. How would mature nonhuman primates perform in this experiment, if there were real food rewards? Based on the literature, would they be expected to perform more like adults and less like children? Relatedly, I wonder how rapidly children would learn if the rewards were more direct and appetitive.

The questions of how nonhuman animals would perform on this task is quite interesting, and could provide valuable insight into human development, but that question is outside of the scope of the current paper. For now, we can only speculate on how an adult primate would perform at this task, but we do have some unpublished data with pigeons (who are known to be neophobic, rather than novelty seeking). Pigeons show a pattern of local optimization. They typically try two, maybe three options, pick the best of those options, and then exploit it almost exclusively for hundreds of trials across many sessions spread over several days. Exploration after the initial few trials is very rare. But, it is important to note that the task for pigeons was more directly rewarding and was appetitive in that they received a food reward after every choice. It would be very interesting to see how an adult primate would perform on a version similar to what was run on humans. The potential limitation that the reviewer notes, however, that children's behavior may be different in this relatively abstract scenario than in a directly rewarding (e.g. immediate appetitive rewards) situation, is important to consider. We add discussion of this limitation and the importance of addressing this issue with future research to the Discussion (pg. 18-19).

In addition, we clarify that children earned one sticker for each 180 candies collected (pg. 8).

Lastly, it could be that the response pattern referred to as exploration in the Baseline condition is not merely due to an underdeveloped attention system, but also due to exploration itself being intrinsically rewarding. Especially if they did not fully understand the symbolism and goal of the task, this might be a default behavior. Would adults show this pattern if they were given a 4-choice selection task with no rewards associated with them? This idea is most intriguing.

We agree with the reviewer that exploration may be intrinsically rewarding (particularly to children), and we find this idea very intriguing as well. We've added text to the Discussion noting this possibility (pg. 19). This idea is completely consistent with our viewpoint, although we also note that the mechanisms driving the particular patterns in children's exploratory choices still require explanation that goes beyond this possibility. The current work represents an attempt to elucidate those mechanisms.



Attentional mechanisms drive systematic exploration in young children

**Nathaniel J. Blanco (nathanblanco@gmail.com)**

Department of Psychology, The Ohio State University  
1835 Neil Avenue, Columbus, OH 43210

**Vladimir M. Sloutsky (Sloutsky.1@osu.edu)**

Department of Psychology, The Ohio State University  
1835 Neil Avenue, Columbus, OH 43210

Running Head: Exploration and Attention

Correspondence:

Nathaniel J. Blanco ([nathanblanco@gmail.com](mailto:nathanblanco@gmail.com)) or Vladimir Sloutsky (Sloutsky.1@osu.edu)

The Ohio State University

Department of Psychology

1835 Neil Avenue

Columbus, Ohio 43210

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**Nathaniel J. Blanco (nathanblanco@gmail.com)**

Department of Psychology, The Ohio State University  
1835 Neil Avenue, Columbus, OH 43210

**Vladimir M. Sloutsky (Sloutsky.1@osu.edu)**

Department of Psychology, The Ohio State University  
1835 Neil Avenue, Columbus, OH 43210

Running Head: Exploration and Attention

Correspondence:

Nathaniel J. Blanco ([nathanblanco@gmail.com](mailto:nathanblanco@gmail.com)) or Vladimir Sloutsky (Sloutsky.1@osu.edu)

The Ohio State University

Department of Psychology

1835 Neil Avenue

Columbus, Ohio 43210

### 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 about the world 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). Interestingly, children's exploration also appears non-random. This is surprising because decision-making research critically distinguishes systematic and directed exploration 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 direct their exploration *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 the 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 predictions for the study were motivated by the hypothesis that children's attention allocation is an important factor driving their choices, and in particular that shifting attention broadly across stimuli (instead of focusing selectively) promotes systematically distributing their 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 options may become increasingly appealing over time. For example, a type of graded novelty preference may be at work; a recently selected option is no longer novel, but the unselected options have been increasing in relative novelty since last being chosen. This tendency, therefore, may enable systematic (i.e., non-random) exploration. This idea shares some similarity to the predictions of the Hierarchical Competing Systems model of the A-not-B task (Marcovitch & Zelazo, 2009), wherein repeated exposure to A trials actually decreases the likelihood of perseverating on the A location in

infants. In adults, the decision process is instead associated with selective attention to (and exploitation of) highly rewarding options.

On the basis of previous work (Blanco & Sloutsky, 2019 *PsyArXiv*; Sumner et al., 2019 *PsyArXiv*), we expected that most children in the Baseline condition would engage in systematic exploration, with few children exploiting the best option. The exact role of saliency on children's choices in the Congruent and Competition conditions could manifest in several ways. One possibility was that children's choices would be driven largely by salience, leading to selecting the most salient option regardless of its reward value. Another possibility 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.

Finally, it was also possible that altering children's attentional pattern through bottom-up capture of attention (disrupting attentional distribution) would also change the very exploratory behavior that gives rise to the pattern of choices observed previously in the Baseline condition. If so, we can infer an important 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 systematic exploratory behavior.

While we expected attention allocation to affect exploratory behavior in young children, the exact role of attention is not known. We therefore expected that the second possibility (i.e., salience as a learning cue) was highly unlikely. At the same time, we considered both attentional hypotheses likely (i.e., salience-based responding (Possibility 1) and salience disrupting systematic exploration (Possibility 3). 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 = 48-67 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,  $X^2(2; N = 110) = 2.01$ ,  $p = 0.367$ . Adults ( $N = 108$ ) 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.

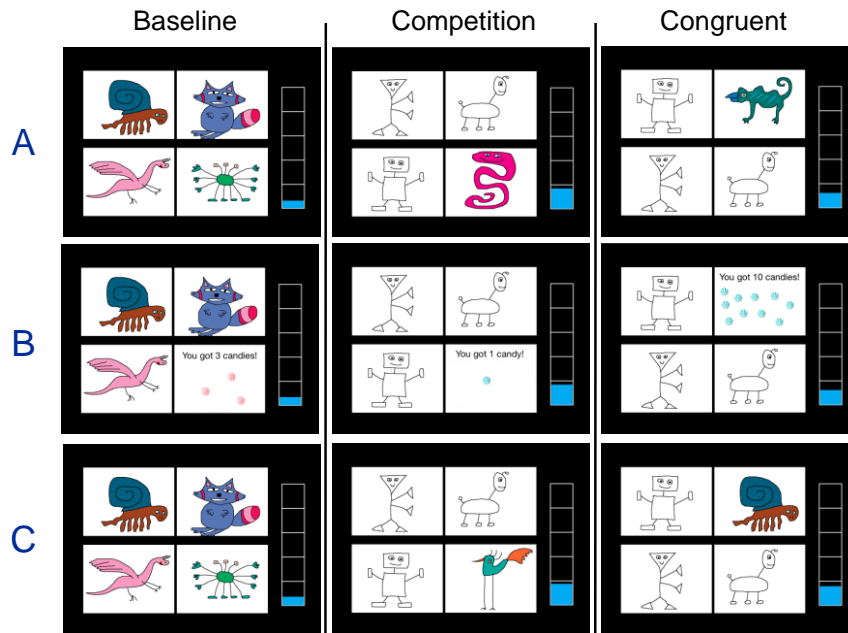


Figure 1: Trial structure. (A) After each choice, (B) the reward earned for the choice was presented for 3 s, (C) then the next trial began. In the Congruent and Competition conditions one option was represented by a colorful image that changed on every trial, while the other three were represented by 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 a sticker for every 180 candies earned, with benchmarks on the meter indicating these goals. The experiment took about 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 3 (Condition: Baseline, Competition, or Congruent) by 2 (Age Group: Children vs. Adults) 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- $\eta^2 = 0.06$ .

To examine the interaction, we conducted separate ANOVAs within each age group. These analyses 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,  $t(72) = 1.50, p = 0.137, d = 0.35$ .

To further test the effects of salience on choice preferences, we analyzed the proportion of choosing the lowest-valued option (which was salient in the Competition condition) across conditions and age groups. A 3x2 (Condition by Age Group) 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,  $t(72) = 1.03$ ,  $p = 0.308$ ,  $d = 0.24$ .

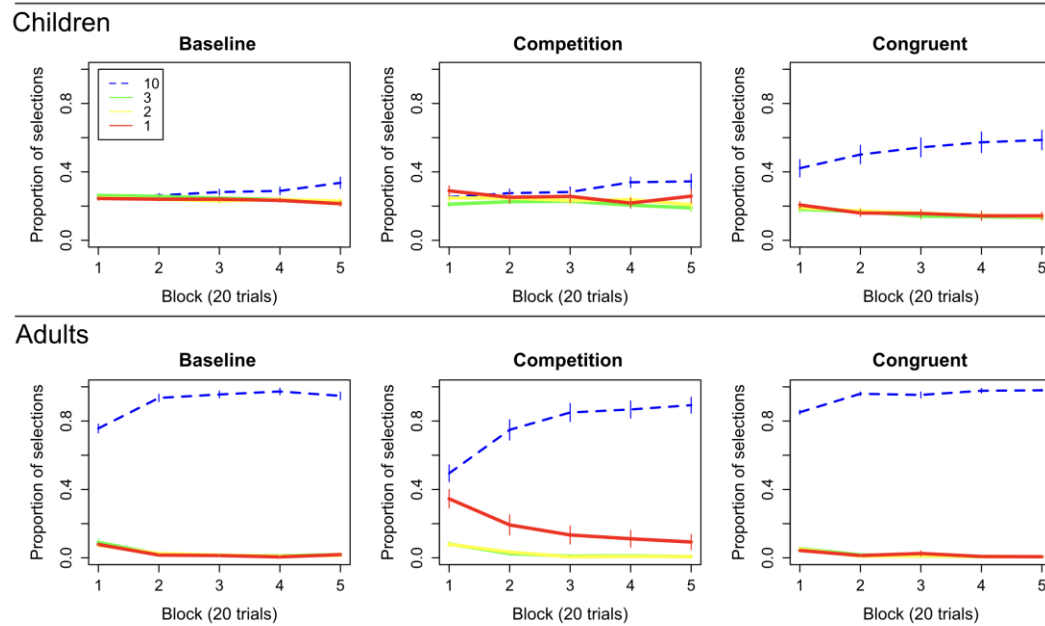


Figure 2: Choice proportions. The proportion of trials on which each option was chosen is presented for blocks of 20 trials. Children in the Congruent condition selected the highest-valued option more frequently than children in both the Baseline and Competition conditions. Interestingly, children in 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.

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. For children, saliency facilitated choosing the highest option more often (and the lowest option less often) in the Congruent condition compared to other conditions. Although these findings are clear, choice proportions present only preliminary (and ambiguous) evidence because the same choice proportions could be generated by different strategies (e.g., random exploration, systematic exploration, or a combination of exploration and exploitation). To eliminate this ambiguity, in the next two sections, we analyze how participants switch among the options across conditions and age groups, followed by computational modeling of their choice strategies.

### *Switch proportions*

To further examine effects of salience, we analyzed the proportion of trials that participants switched responses, choosing a different option than on the previous trial, as an indicator of elevated exploration (Figure 3). Typically, when outcomes are stable, low levels of exploration are expected (Knox et al., 2012; Otto et al., 2014), however, based on recent evidence (Blanco & Sloutsky, 2019 *PsyArXiv*), we expected children to switch often, suggesting a high level of exploration. Furthermore, subsequent computational modeling (Blanco & Sloutsky, 2019 *PsyArXiv*), indicated that this exploration was highly systematic. We, therefore, first focus on participants' switch responses across conditions, following by modeling of their choice strategies.

A 3x2 (Condition by Age Group) 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,  $F(2,105) = 1.90, p = 0.154, \eta^2 = 0.03$ .

By contrast, 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 choices of the best option. To examine the underlying choice strategies, we performed computational modeling presented in the next section.

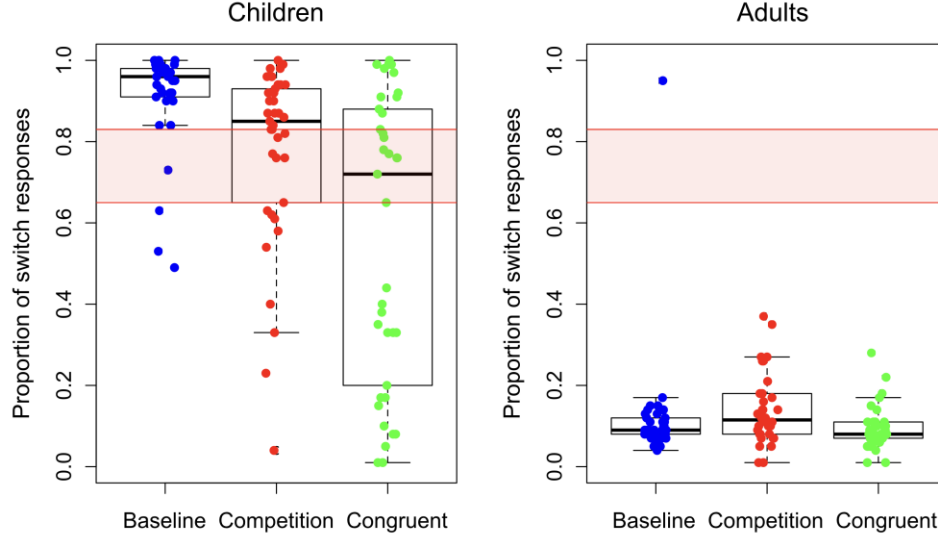


Figure 3: Response Switching. The proportion of trials on which participants made a switch response, choosing a different option than the previous trial, is presented. The pink shaded region represents 95% probability density of switch responses given random responding. Extreme switch proportions for 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 strategies driving participants’ choices across the conditions, we evaluated these choices 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:

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

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  $\alpha$  is the learning rate (a free parameter). It then made choices according to the following function:

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

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  $\phi$  ( $0 \leq \phi \leq 1$ ) mediates the relative weights of expected values (i.e. exploitation) and lags (i.e. systematic exploration) in determining choices. Greater values of  $\phi$  indicate greater influence of systematic exploration. When  $\phi = 0$ , the model chooses based only on expected value; when  $\phi = 1$ , it chooses only based on the lag.  $\phi = 0.5$  represents roughly equal contributions of reward value and choice lag.  $\beta$  is the inverse temperature parameter that controls random exploration. At  $\beta = 0$  choice probabilities become completely random (i.e. equal between all options). As  $\beta$  approaches infinity the model chooses the most favorable option (based on the weighted combination of value and lag described above) on every trial.  $\beta$  and  $\phi$  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 (Condition by Age Group) ANOVA on best-fitting  $\phi$  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  $\phi$  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  $\phi$  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 (Condition by Age Group) ANOVA on best-fitting  $\beta$  (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- $\eta^2 = 0.003$ .

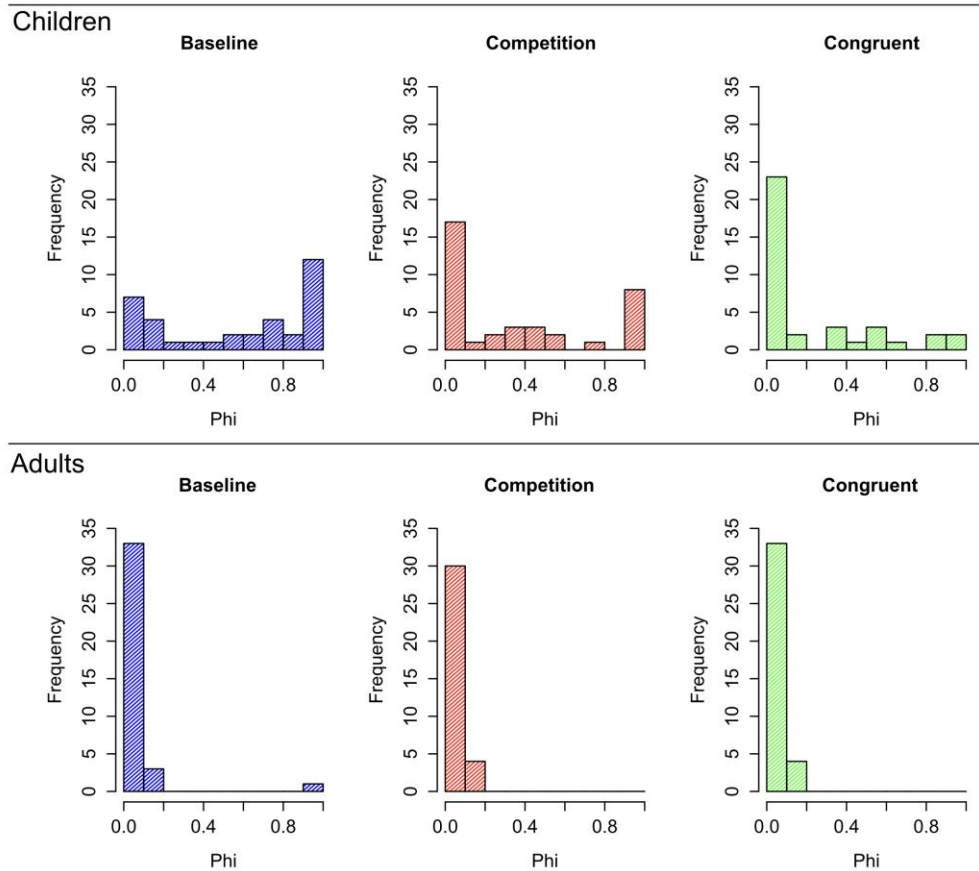




Figure 4: Best-fitting  $\phi$  parameter. Histograms of the best-fitting  $\phi$  parameter for each group are presented. Both salience conditions had a large proportion of children with very low values of  $\phi$ , indicating little systematic exploration, while the Baseline condition had a larger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

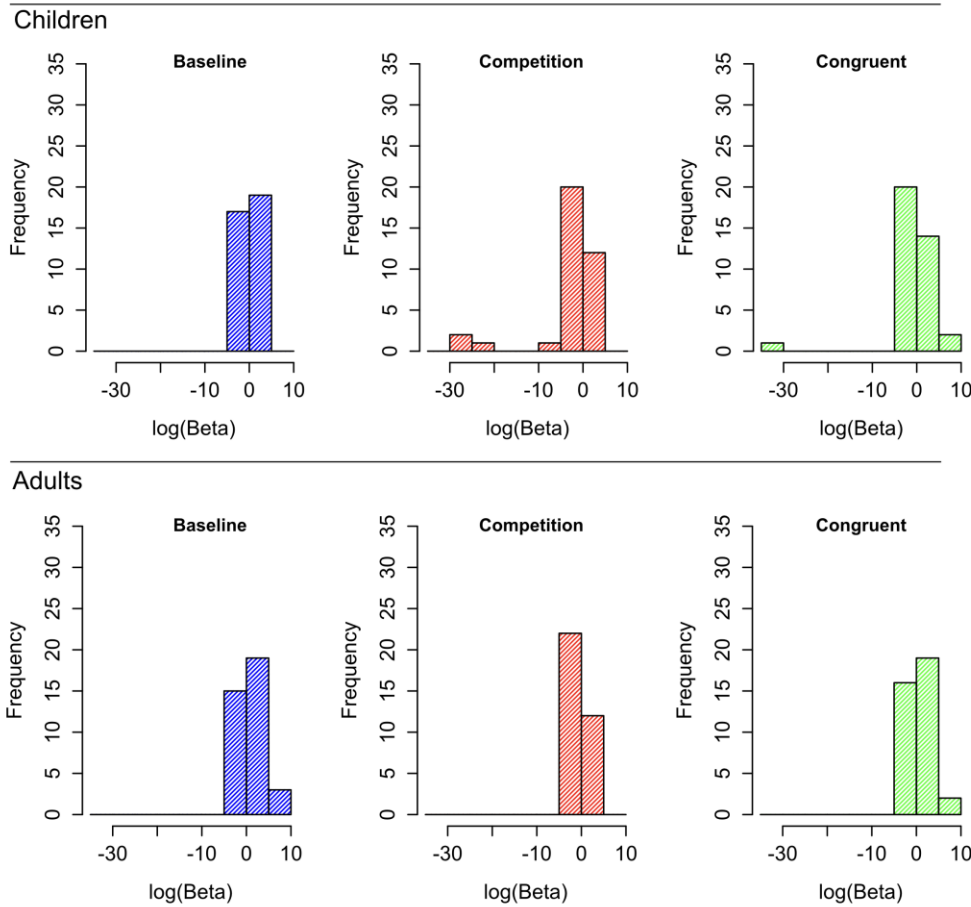


Figure 5: Best-fitting  $\beta$  parameter. Histograms of the log of best-fitting  $\beta$  (which controls the rate of random exploration) are presented.  $\log(\beta)$  is presented rather than raw values because large outliers make graphing the raw values difficult. There were no significant age or group effect on best-fitting  $\beta$  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 the strategies underlying their choice patterns. The results suggest that attentional manipulation (i.e., exogenously capturing attention through large differences in salience) decreased the level of systematic (i.e. non-random) exploration in young children compared to a Baseline condition—where they were systematic and highly exploratory. Children in the Competition and Congruent conditions switched between options less often, and did so less systematically, than children in the Baseline condition. The difference is particularly striking in the Competition condition where choice proportions were equivalent to the Baseline condition. These differences suggest that the effect of salience on children's attention caused an important change in how they were making decisions. 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, while children's choice preferences were not simply salience-driven (the effect of saliency was dependent on whether or not salience was congruent with reward value), the underlying choice strategy revealed by computational modeling was driven by salience. Whereas high levels of systemic exploration were observed in children in the Baseline condition, these levels were substantially lower in the Congruent and Competition conditions. In the Competition condition we found elevated levels of random exploration, whereas in the Congruent condition, there were higher levels of exploitation, compared to the Baseline condition.

These results suggest a potentially integral role of children's immature attentional allocation in facilitating systematic exploration—in contrast to adults' tendency to both

selectively attend and maximize reward. Under normal circumstances, systematic exploration is children's default strategy. Less recently sampled options become more likely to be selected in the future—a pattern that may effectively approximate uncertainty-directed exploration in many cases. We suggest 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 and be chosen). Manipulating bottom-up attention by altering the relative saliency of the choice options disrupts this process, leading to a reduction in systematic choice patterns.

### *Unanswered Questions and Future Directions*

While the current results indicate there may be an important connection between children's attention and their systematic exploratory behavior, the current study leaves a number of questions to be addressed in future research. For example, we did not directly measure participants' attention allocation during the task. While children's tendency to distribute attention broadly and its effects on cognition have been previously shown in other tasks (e.g. Deng & Sloutsky, 2015, 2016), it is possible that children exhibited focused attention during this task. If so, it could be that the mismatch between salience and reward in the Competition condition caused children confusion as to the goal of the task, leading to more random responding (and hence less systematic behavior). In that case, though, we might expect that children would explore the salient option more often to reduce their confusion, which we did not observe. Still it remains possible that the difference in children's behavior was the result of other mechanisms than a disruption to their default distributed attention allocation pattern. Future work that measures children's attention directly (e.g. with eye-tracking) will be needed to better understand the exact role that attention contributes to children's choices. Another potential limitation of the current

study is the relatively abstract nature of the rewards. It is possible that children's behavior may be different in a scenario where rewards are more direct and immediate, such as directly foraging for food rewards, rather than collecting virtual points that eventually earn real stickers. Investigating exploratory behavior in children in that type of situation could be an insightful area for future research. Finally, while the results implicate an important role of attention, it is possible that other factors also contribute to children's exploratory behavior. For example, exploring may also be more intrinsically rewarding to children compared to adults. Such intrinsic enjoyment of exploration coupled with graded novelty preference would also result in systematic exploration. However, in this case, it is not clear why salience would disrupt the intrinsic value of exploration.

### *Conclusions*

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. In particular, children's tendency to distribute attention broadly may be tied to their tendency to explore systematically. Children's increasing ability to attend selectively may then 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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### **Open Practices Statement**

The data reported in this paper is archived and available on Open Science Framework at <https://osf.io/ph9kz/>.

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**Nathaniel J. Blanco:** Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Review & Editing, Visualization, Supervision, Project administration **Vladimir M. Sloutsky:** Conceptualization, Methodology, Writing – Review & Editing, Supervision, Project administration, Funding acquisition