

Exploration and Attention in Young Children

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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 general knowledge about the world. Theories of decision-making describe systematic exploration as a computationally refined capacity, primarily sub-served by prefrontal cortex (PFC). We recently demonstrated that systematic exploration predominates young children's choices, despite immaturities of PFC early in development. We hypothesize that rather than being driven by PFC-mediated processes, like adults, systematic exploration in young children is driven by attentional mechanisms. We test this hypothesis using a simple task where children chose between four options and received rewards. Saliency was manipulated such that it was either congruent with or in competition with maximum reward. Rather than simple novelty-seeking, saliency interacted with reward. Saliency disrupted systematic exploration, while also facilitating reward maximization in the congruent condition. These results suggest a close relationship between attention and systematic exploratory behavior in young children.

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

Introduction

One crucial way in which children's cognition differs from adults' is how they allocate their attention. Adults are highly adept at controlling their attention, distributing it or focusing it selectively while ignoring other information. While adults tend to rely heavily on selective attention, young children tend to distribute their attention broadly (Deng & Sloutsky, 2015, 2016; Smith & Kemler, 1977). In situations in which only a small amount of the available information is relevant at the moment, adults will selectively focus on that piece of information, and ignore almost everything else (Rehder & Hoffman, 2005; Blair, Watson & Meier, 2009). Children, on the other hand, will distribute their attention to everything, even information that is not relevant for their current task or goals (Plebanek & Sloutsky, 2017). The question then becomes: why do children seem to use a strategy that is clearly less efficient and potentially less effective? One simple explanation could be that young children simply do not have the ability to control their attention effectively, to focus it selectively and filter out irrelevant environmental stimuli. While it is likely the case that children's ability to control attention is highly limited, there is emerging evidence that such limitation can be adaptive.

While adults' utilization of selective attention is often highly effective and efficient, distributing attention can sometimes result in superior performance. For example, Plebanek and Sloutsky (2017) found developmental reversals in a change detection task—where children were better than adults at detecting changes in uncued items—and in a visual search task—where, in a surprise subsequent memory test, children outperformed adults on memory for specific features that were irrelevant to the main search task.

Whether selective or distributed attention is advantageous is context dependent. Selective attention is advantageous when one is confident that a small portion of the available information is sufficient to achieve their goals and that other available information is superfluous. Distributed attention is advantageous when there is more uncertainty about what is and is not important. For young children, who have much less experience and knowledge about how things in the world work, distributing attention may often be the best strategy. Besides just being a safer bet, by broadly gathering information it facilitates the important long-term goal of building up that rich general knowledge that adults rely on later in life. In other words, distributed attention may subserve exploration. By distributing attention early in life children may be sacrificing immediate benefits in exchange for information that can be used later.

Research on exploratory behavior makes an important distinction between systematic and undirected exploration strategies (Badre, Doll, Long, & Frank, 2012; Daw, O'Doherty, Dayan, Seymour, & Dolan, 2006; Knox, Otto, Stone, & Love, 2012; Blanco, Love, Cooper, McGeary, Knopik, & Maddox, 2015; Somerville, Sasse, Garrad, Drysdale, Abi Akar, Insel, & Wilson, 2017). Ideally exploratory choices are most valuable when they are systematically directed towards actions with greater uncertainty in their outcomes, as resolving that uncertainty gives the most information. Mounting evidence suggests an important role of prefrontal cortex in this type of exploration (Badre, Doll, Long, & Frank, 2012; Frank, Doll, Oas-Terpstra, & Moreno, 2009; Blanco et al., 2015; Otto, Knox, Markman, & Love, 2014). Conversely, undirected (or random) exploration can be achieved as the simple outcome of a stochastic decision-process, with much less reliance on prefrontal cortical processing. Given that prefrontal cortex shows substantially protracted development (Sowell, Thompson, Leonard, Welcome, Kan, & Toga, 2004; Sowell, Thompson, Holmes, Jernigan, & Toga, 1999), current

theories make a straightforward prediction that young children's exploration should be largely unsystematic (Somerville et al., 2017).

In contrast to this straightforward prediction, we recently showed that four-year-olds' choices are highly exploratory, and this exploration is largely systematic (Blanco & Sloutsky, under review). Because of the immaturity of PFC in young children, we hypothesize that their exploratory behavior is instead tied intricately to their immature attention allocation, consistent with recent research suggesting a tight link between attention and decision-making (Gottlieb, 2012; Kononov & Krajbich, 2016).

To test this hypothesis more directly, in the current study we presented children with a simple reward learning task. Our task was a simplified version of a standard n -armed bandit task commonly used to study reward-based decision-making (e.g., Daw et al. 2006). On each of 100 trials, participants chose one of four options which gave set reward values (10, 3, 2, and 1) that were stable across the experiment and highly separable. Because outcomes are stable and predictable, low levels of exploration would generally be expected, but our previous study found high levels of systematic exploration in young children in this task.

Crucially, in the current study we also manipulated the perceptual saliency of stimuli marking the options. In the two reported conditions, three options were represented by bland, stable stimuli, while one option was represented by a highly salient stimulus that changed on every trial. In the *congruent* condition the salient option was also the one that gave the highest reward. In the *competition* condition the salient option was the one that gave the lowest reward, putting reward-seeking and novelty-seeking in competition with each other.

There are several potential competing hypotheses concerning the relationship between attention and choices in young children. One possibility is that children's choices are driven largely by novelty seeking, rather than reward seeking, resulting in elevated exploration levels. In that case we would predict children to choose the salient option most often, regardless of whether it is congruent with or in competition with maximum reward value. A contrasting prediction is that children's choices are not controlled by attentional mechanisms, but instead their elevated exploration is driven by other processes—for example, an explicit goal-directed strategy to seek information, or even a simple behavioral drive for variability in action selection. In such cases we would expect a small effect of saliency, if any, which should be similar across both conditions.

A third class of predictions involves an interaction between saliency and reward, wherein the effect of the salient option is different depending on whether it is congruent or competing with reward. For example, saliency may facilitate memory, leading to better learning of the best option in the congruent condition and more avoidance of the worst option in the competition condition. We suggest that attentional mechanisms may be specifically tuned to facilitate learning in young children, generally resulting in high levels of

exploration in many cases. But exogenously capturing attention, as in the current experiment, may interfere with systematic exploration by drawing attention to the salient option rather than to less recently sampled options—which we suspect is a crucial aspect of young children's systematic exploration.

Methods

Participants A total of 80 four-year-olds (mean age = 55 months) participated in the experiment: 23 in the congruent condition, 25 in the competition condition, and 32 in the baseline condition. Participants were recruited from preschools and childcare centers in the Columbus, Ohio area.

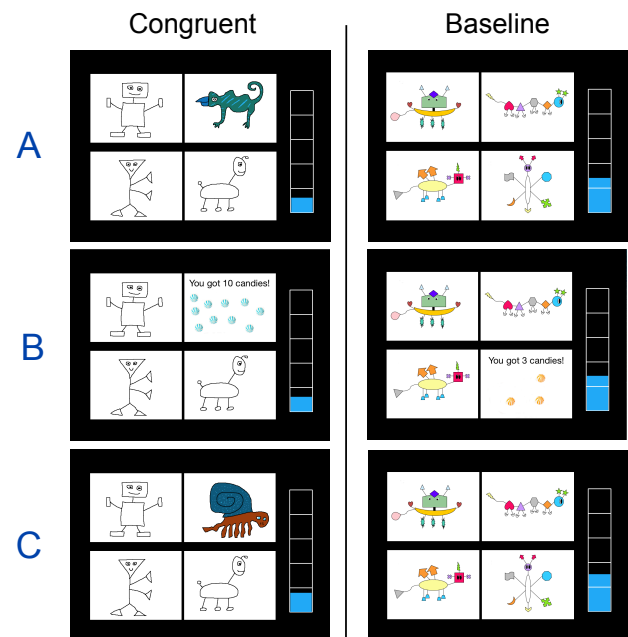


Figure 1: Trial structure. (A) After each choice, (B) the reward earned for the choice is presented for 3 s, (C) then the next trial begins. In the congruent and competition conditions one option is represented by a colorful image that changes on every trial, while the other three are represented by lower saliency images that remain stable across trials. In the baseline condition, all four options are represented by stable images of equal saliency.

Procedure Participants completed a simple decision-making task that was framed as a computer game in which they asked alien creatures for candy (Figure 1). The goal of the game was to earn as much candy as possible. On each trial (of a total of 100 trials), participants chose one out of the four creatures and received (virtual) candy for their choice. Selections were made using a touch screen. Each creature gave a set number of candies that was the same on every trial. One option gave 10 candies, while the other three options gave 3, 2, and 1 candies respectively. The locations of the reward values were

stable across the entire experiment, but were randomly determined for each individual participant. Following the choice, the reward received for the choice was displayed for 3 s (Figure 1B). Then a meter that tracked the total accumulated reward was updated. Children were given tangible rewards (stickers) for each 180 candies earned, with benchmarks on the meter indicating these goals. When a goal was reached, a congratulatory screen appeared telling the participant that they earned a sticker.

Participants were assigned to one of three conditions: congruent, competition, and baseline. In the congruent and competition conditions, perceptual novelty and saliency were manipulated. Three of the four creatures were simple black and white stick figures while one was colorful and perceptually rich. In addition, on each trial the salient image changed to a new novel creature (Figure 1C). In the congruent condition, the salient option was mapped to the highest reward value (10 candies). In the competition condition, the salient option was mapped to the lowest reward value (1 candy), putting reward and perceptual novelty in competition. In the baseline condition, all four options had equal perceptual saliency, and the images were stable across all trials of the experiment.

Behavioral Results

Participants' choices over the course of the experiment were analyzed (Figure 2). In particular performance was analyzed as the proportion of trials on which the highest valued option was chosen. An ANOVA revealed a significant effect of condition, $F(2, 77) = 7.40, p = 0.001, \eta^2 = 0.16$. Pairwise comparisons showed that participants in the congruent condition chose the best option significantly more often than participants in the baseline condition, $t(53) = 2.13, p = 0.038, d = 0.58$, and the competition condition, $t(46) = 3.80, p < 0.001, d = 1.10$. In addition, performance in the competition condition was marginally lower than the baseline condition, $t(55) = 1.97, p = 0.053, d = 0.53$. Importantly, the proportion of trials in which the lowest valued option (which was salient in the competition condition) was chosen did not differ by condition, $F(2, 77) = 2.24, p = 0.114, \eta^2 = 0.002$. This pattern of results suggests that perceptual saliency facilitated reward optimization in the congruent condition, but not through simple novelty-seeking since the salient option was not selected more frequently in the competition condition.

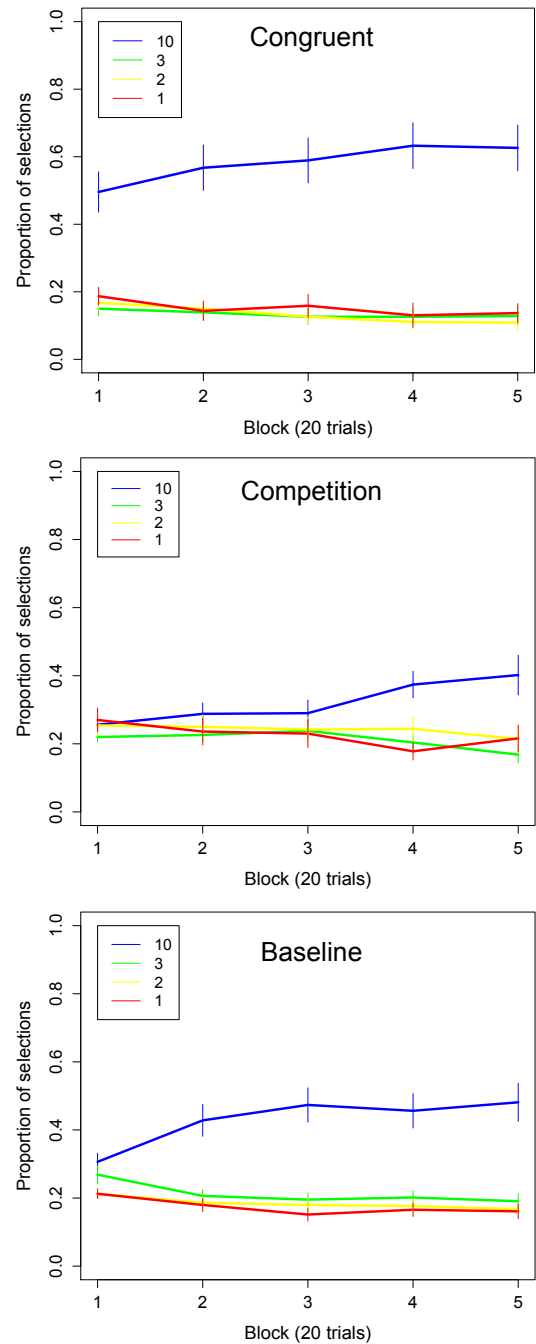


Figure 2: Choice proportions. The proportion of trials on which each option was chosen is presented for blocks of 20 trials. Compared to baseline, children in the congruent condition selected the highest valued option more frequently. Children in the competition condition selected the highest valued option less often than either the baseline or congruent 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 other conditions where it was less salient. This suggests that pure novelty/saliency seeking did not drive children's choices. Error bars reflect standard errors of the mean.

Computational Modeling

In order to better understand children’s choice strategies, and to examine the effect of the saliency manipulation of directed exploration, participants’ choices were evaluated in relation to a Reinforcement Learning model (Sutton & Barto, 1998) that included the potential for both systematic (or directed) and random exploration. The model learned the reward values by updating expected values for each option based on the prediction error 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 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:

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

where $P(a_{i,t})$ is the probability of choosing option i on trial t . $L_{i,t}$ is the lag term—a proxy for uncertainty—that simply encodes the number of trials it has been since option i was last chosen. ϕ is the weight parameter mediating the relative extent to which the expected values and lags influence choices and is constrained to be between 0 and 1, inclusive. Greater values of ϕ indicate greater influence of systematic exploration. When ϕ is 0, the model chooses based only on expected value; when ϕ is 1 it chooses only based on the lag. β is the inverse temperature parameter that controls random exploration. At $\beta = 0$ choice probabilities become completely random, and as β approaches infinity the model chooses the most favorable option (based on the weighted combination of expected value and lag described above) on every trial. Both β and ϕ were free parameters.

This model is similar to the ‘exploration bonus’ models used in some previous studies (Daw et al. 2006, Kakade & Dayan, 2002), but with lag as a proxy for uncertainty and with slightly different parameterization. The model was fit to each individual participant by finding the set of parameters that maximized the likelihood of producing the participant’s data given the model.

Modeling Results

The best-fitting parameter values were compared between the three different conditions. Because the best-fitting parameter values were not normally distributed we examined median values, which are listed in Table 1. The high value of ϕ in the baseline condition suggests a large influence of systematic exploration on choices. The median value of ϕ was substantially lower in both the congruent and competition conditions compared to baseline, suggesting much lower levels of systematic exploration in these two conditions. While performance suggests that in the congruent condition systematic exploration was largely replaced with reward

maximizing choices, in the competition condition a low value of β suggests a greater amount of random exploration in that condition.

Table 1: Median best-fitting parameter values (with standard deviations in parentheses)

	Congruent	Competition	Baseline
ϕ	0.045 (0.35)	0.023 (0.44)	0.419 (0.40)
β	0.775 (74)*	0.277 (2.7)	0.689 (39)*

*Note: While the medians suggest most values were small, β has no upper limit, and infrequent large outliers (which are consistent with reward maximization) result in large standard deviations for β .

Discussion

In this study, we examined the effects of an attentional manipulation on young children’s choices and exploratory behavior. Our results suggest that including an option that is much more perceptually salient than the others decreases the level of systematic exploration that young children exhibit, compared to a baseline condition. In addition, children’s choices did not indicate that they were simply novelty-seeking in their choice strategy. Instead the effect of saliency was dependent on whether or not it was congruent with or in competition with reward maximization. When the salient option was also highly valuable, children chose that option more often than in the other conditions. But, when the salient option was low in value, it was not chosen any more often than in the other conditions. This interaction suggests a more complicated role of attention in determining young children’s choices. While its exact role requires further study to be determined, saliency appears to act as a type of cue that can facilitate learning under the right circumstances.

Together these results suggest that attentional mechanisms are a major determinant of exploratory behavior in young children. When saliency and/or novelty are otherwise equal, systematic exploration dominates choices, with options that were less recently sampled being more likely to be selected. Asymmetry in salience/novelty seems to disrupt this process, leading to relatively less systematic exploration. Once disrupted, if the salient stimulus signals a rewarding option, it can act as a cue that facilitates learning. If not, children seem instead to revert to a random exploration strategy.

These results point to an integral role of attentional mechanisms in systematic exploratory behavior in young children, in contrast to the top-down PFC mediated processes involved in systematic exploration in adults. Despite PFC being immature, young children’s distributed attention allocation pattern seems to support systematic exploration, which may be critical in enabling broad information gathering during the early stages of life.

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