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Changes in Adaptation to Time Horizons across Development

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Abstract

When making decisions, the amount of time remaining matters. When time horizons are long, exploring unknown options can inform later decisions, but when time horizons are short, exploiting known options should be prioritized. While adults and adolescents adapt their exploration in this way, it is unclear when such adaptation emerges and how individuals behave when time horizons are ambiguous, as in many real-life situations. We examined these questions by having 5–6 year-olds (N=43), 11–12 year-olds (N=40), and adult college students (N=49) in the United States complete a Simplified Horizons Task under Short, Long, and Ambiguous time horizons. Adaptation to time horizons increased with age: older children and adults explored more when horizons were Long than when Short, and while some younger children adapted to time horizons, younger children overall did not show strong evidence of adapting. Under Ambiguous horizons, older children and adults preferred to exploit over explore, while younger children did not show this preference. Thus, adaptation to time horizons is evident by ages 11–12 and may begin to emerge around 5–6 years, and children decrease their tendencies to explore under short and ambiguous time horizons with development. This developmental shift may lead to less learning but more adaptive decision-making.

Keywords

explore-exploit; decision making; development

To achieve our goals, we often must make decisions that do not produce immediate outcomes. In these situations, future time horizons–the expected amount of remaining time to achieve a goal–play an important role in determining the best decisions to make. For example, to get good coffee, we may explore different coffee shops around town to find the best brew. However, if we are only passing through town for a short time, we may forgo exploration and opt for a familiar brew from a familiar chain. Adapting exploration to time horizons constitutes an important part of adaptive decision-making.

Formal models show that to maximize long-term gain, a decision-maker should strategize based on expected time horizons (Weenig & Maarleveld, 2002; Rich & Gureckis, 2018),

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This study was not preregistered.

exploring more when horizons are long and less when short. Empirical studies have used the Horizons Task to assess how people adapt to time horizons (Wilson et al., 2014). In this computerized task, participants have a limited number of opportunities on each trial to win points from two slot machines. Each trial presents two new slot machines that differ in their pay-out average, pay-out variance, and amount of uncertainty about those pay-outs. Under long horizons, participants are allowed six choices to gather points, while under short horizons, only one choice is allowed. Adults choose the more uncertain slot machine more often under long horizons than under short horizons (Wilson et al, 2014; Rich & Gureckis, 2018), demonstrating adaptation to time horizons. Further, adaptation in adults is associated with less temporal discounting and greater valuation of future over present rewards (Sadeghiyeh et al., 2020). Given the value of adapting and its links with future-oriented behaviors, it is important to understand when and how adaptation to time horizons emerges during development.

Do time horizons affect children's exploration? The current literature is unclear. Children are naturally exploratory (Kidd & Hayden, 2015) and can shape their decisions based on expectations about the future, which suggest that children may adjust their exploration based on time horizons. For example, children show more directed exploration towards uncertain options than adults, suggesting a heightened valuation of information over reward (Schulz et al., 2019). Preschoolers can also deploy rudimentary future-oriented thinking skills, selecting appropriate items for future events (Moffett et al., 2018) and planning for multiple future possibilities in laboratory tasks (Atance et al., 2015; Seed & Dickerson, 2016). Performance in these laboratory tasks improves across childhood (Ferretti et al., 2018). Moreover, children opt for immediate rewards over future rewards when the promise of a future reward is not reliable (Kidd et al., 2013; Michaelson & Munakata, 2016). These findings suggest that children are exploratory and sensitive to environmental conditions with implications for the future and can adjust their behavior accordingly.

However, the available empirical evidence also suggests children struggle to adapt to time horizons. In one study, preference for exploring the more uncertain option under long compared to under short horizons emerged and increased across ages 12–28 years, suggesting that adaptation to time horizons improves throughout adolescence into young adulthood (Somerville et al., 2017). However, in the horizons task used in that study, uncertainty was presented at multiple levels (e.g., uncertainty varied between and within options), which may have made it challenging for younger adolescents to integrate this information and strategize accordingly. Another study varied time horizons in a task with 8–9 year-olds and found limited adaptiveness when horizons were short; however, analyses were not reported comparing different time horizons (Lindow & Betsch, 2019). Moreover, both studies used tasks with numeric components that might pose challenges for younger children and obscure their ability to adapt. This leaves open the possibility that young children can adapt to time horizons in simpler task environments.

We build on this work by addressing two questions to further our understanding of developments in children's adaptation to time horizons. First, given that tasks used in previous investigations may have been complex, a simpler task might be needed to reveal adaptive exploration in younger children. We investigate this possibility using a Simplified

Horizons Task with clear explore and exploit choices with three age groups: adults (to test replicability of prior findings with a new paradigm), 11–12 year-olds (to test whether a simplified task elicits adult-levels of adaptive exploration, counter to prior findings), and 5–6 year-olds (to test adaptive exploration during an even earlier stage of development, when children show notable improvements in cognitive processes such as proactive control (Lucenet & Blaye, 2014) that support anticipating future states (Braver, 2012) and adapting to time horizons).

Second, time horizons can be ambiguous. Adults consider this time ambiguity—uncertainty about when an event will occur—aversive (Ikink et al., 2019). In an information-seeking task where time horizons were ambiguous, adults preferred to sample more familiar, commonly occurring options over more rare options (Rich & Gureckis, 2018). This might suggest that adults reduce their exploration under ambiguous future horizons. However, in that task, the value of information was manipulated via item frequency, such that it was adaptive to sample more familiar items over less familiar ones. Moreover, it remains unclear how ambiguous horizons affect exploration in the most basic sense, when the options are simply between explore and exploit. Do individuals adapt to ambiguous time horizons by preferring to exploit known options? Further, how do preferences change across development? Some evidence suggests that adolescents are less averse to ambiguity than younger and older individuals (van den Bos & Hertwig, 2017), suggesting that responses to ambiguity change across development. We investigate these questions by assessing tendencies to explore and exploit under ambiguous time horizons across age groups.

Methods

Participants

Participants were recruited from Boulder, CO, United States and surrounding areas, from the University of Colorado Boulder's Department of Psychology and Neuroscience adult participant pool and child participant database. Three groups participated: younger children aged 5–6 years (mean=5.5 years, males=24, females=19, N=43), older children aged 11–12 years (mean=11.5 years, males=23, females=16, unknown sex=1, N=40), and adults aged 18–31 years (mean=19.4 years, males=14, females=35, N=49). The self- or parent-identified racial composition of our sample was approximately 79% White, 1% Black, 3% Asian, 8% mixed race, 2% unknown, and 8% unreported; a total of 7% reported Hispanic or Latino ethnicity. We aimed to recruit 60 participants per age group to recover an estimated age effect size of Cohen's d>0.8 with 95% power; however, recruitment was halted by the COVID pandemic, thus resulting in our final recruitment numbers. Adults received partial course credit and families of children received $10 and a token for participating. All adults and parents of children provided informed consent, and all children provided verbal assent prior to participation. All procedures were approved by the University of Colorado Boulder's Institutional Review Board (Protocol #19–0039). For the Horizons task, 3 younger children were excluded due to incompletion, and 1 adult was excluded due to technical issues. The final usable Ns were Younger Children=40, Older Children=40, and Adults=48.

Procedure

Study procedures were administered in a testing room with minimal distractions. The experimenter was present throughout the experiment for all participants regardless of age. All participants completed the Simplified Horizons Task, followed by the AX-Continuous Performance Task (AX-CPT; adapted from Chatham et al., 2009), and an age-adapted parent- or self-report Intolerance of Uncertainty Scale (IUS; Carleton et al., 2007; Comer et al., 2009). Details about the AX-CPT and IUS and their results can be found in Supplementary S6. Children also completed an effort-based information sampling task not part of this paper's aims.

Measures

Simplified Horizons Task—To assess individuals' adaptation to time horizons, we developed a child-friendly Simplified Horizon Task (Figure 1, based on the Horizon Task; Wilson et al., 2014). In this task, participants played a computerized game in which they made a series of explore-exploit decisions under different time horizons. Participants were first introduced to an artist who needed help finding paint. To assist the artist, participants visited paint stores. At each store, participants chose among four options of paint canisters that each contained a different-sized paint splash. Adjacent reward sizes on the same trial differed from each other by a ratio randomly sampled from 1.5 to 2.5, a size difference perceivable by young children and adults (Henik et al., 2017; Sweeny et al., 2015; see Supplementary S1 for details of reward size magnitudes). The task was to collect as much paint as possible from these canisters. Participants were informed that a canister could be selected multiple times in a trial and that each selection always yielded the same amount of paint.

At the start of each trial, the amount of paint of one canister was shown, and those of the other three canisters were obscured by a question mark. To adjust the information value of canisters in a trial, participants first completed a fixed-choice portion (Fig. 1A). In this fixed-choice portion, participants were directed to sample from and collect paint from two of the three obscured canisters, which were indicated in sequence by hand figures that appeared on the canisters. Participants collected paint by clicking on a canister with the mouse or pointing for 5–6-year-olds (as some were unfamiliar with using a computer mouse). Once an obscured canister was selected, its paint splash size was revealed and could be resampled through the remainder of the trial. Thus, the fixed-choice portion ended with four canisters with different sized paint splashes, three of which were visible and one still obscured. The canister with the largest visible paint splash was the Exploit option, the canister with the obscured paint splash was the Explore option, and the remaining two canisters were the Other options.

Next, participants proceeded to the free-choice portion of the trial (Fig. 1B). Before freely choosing among the four options, participants were informed of the number of "picks" or free-choices remaining for this trial. This served as the time horizon manipulation. Participants were either given four free-choices (Long Horizon), one free-choice (Short Horizon), or an unknown number of free-choices (Ambiguous Horizon; the actual number of free-choices could be either 1 or 4). The horizon information was presented pictorially by the number of hand figures on the center of the screen and verbally announced by the experimenter before beginning the free-choice portion. The goal was to collect as much paint as possible over the free-choices collectively. The trial terminated when the participant used up all their free-choices, and participants then automatically proceeded to the next trial.

Before beginning the test trials, the experimenter demonstrated a trial and highlighted the task structure and rules. The experimenter also asked comprehension questions to ensure that the participant understood key task rules (that a canister can be picked multiple times without diminishing rewards, the difference between fixed- and free-choice portions, and the horizons information in each trial). Participants then completed 4 practice trials before beginning the 18 test trials, with 6 trials per horizon condition. Trial order was randomized among the three horizons conditions and fixed across participants. The exploit option was the reward maximizing option on the majority of the test trials (15/18 trials, close to the ¾ trials that would be expected by chance given that exploit options were three times more common than explore options), as opposed to explore and exploit options being similarly reward maximizing, a point we address in the Results.

The main outcome of interest in each trial is the participants' initial free-choice: Explore, Exploit, or Other. This outcome reflects a choice in response to the time horizons manipulation in each trial and showed good internal reliability for each of the three horizons conditions (Long α=0.759, Short α=0.724, Ambiguous α=0.798). To examine individual differences in adaptive exploration, an Adaptive Exploration score was calculated for each individual (Adaptive Exploration= %Explore in Long Horizons - %Explore in Short Horizons); higher values reflect more adaptation to time horizons (Figure S2).

Finally, participants were asked to indicate whether they preferred exploring ("opening covered cans") or exploiting ("getting big paint splashes"). Their responses are described in Supplementary S4.

Transparency and openness

We report how we determined our sample size, all data exclusions (Table S2), all manipulations, and all measures in the study, and we follow journal article reporting standards (JARS; Kazak, 2018). All data and analysis code (conducted in R version 4.1.0) are available at https://github.com/wwzhuang/horizons. This study's design and analysis were not preregistered.

Data Analysis

Table 1 shows descriptives and correlations by age group, and Figure 2 shows overall levels of initial choices across all participants. Trials from all subjects who complied with task instructions, completed the task, and experienced no technical issues were included. Because of the low number of Other initial choices (70 of 2295 trials), we only include trials with Explore or Exploit initial choices in the main results and separately investigate Other initial choices in Supplementary S2. To test our main questions, we fitted a mixed effects logistic regression predicting Explore initial choices with Horizons (Long, Short, Ambiguous), Age (Younger, Older, Adults), and their interaction as dummy-coded predictors. Because the Exploit option was the reward-maximizing option on most trials, we also included the size of the exploit option of each trial and its interaction with Age in follow-up exploratory models to test age-related effects of visible reward sizes. Predictors were modeled as fixed effects and intercepts were modeled as randomly varying across individuals.Details about this statistical model and its full results can be viewed in Tables 2–5.

We first examined adaptive exploration–first choices under Long and Short horizons–across age groups, and then examined subsequent choice patterns under Long Horizons.. Next, we assessed how the size of the exploit option affected initial choices across age groups, and controlled for its effects on adaptive exploration. Finally, we investigated choices under Ambiguous Horizons. Investigations of additional aspects of the explore-exploit choices and individual differences with proactive control and intolerance of uncertainty can be found in Supplementary S1 - S6.

Results

Adaptation to Time Horizons

First, we tested for differences in Explore initial choices between Short and Long Horizons to assess adaptive exploration. The mixed effects logistic regression predicting Explore initial choices in Long and Short Horizon trials revealed a significant Age X Horizon interaction, $\chi^2(4)=32.33$, $p<.001$ (Table 2). Inspecting Long vs. Short Horizons contrasts by age group (Table 4), a significant preference to explore in Long than in Short Horizons was found in Younger Children (OR=2.409, 95%CI [1.45, 4.00], z=3.39, $p=.002$), Older Children (OR=18.205, 95%CI [10.90, 30.41], z=11.084, $p<.001$), and Adults (OR=11.16, 95%CI [6.98, 17.85], z=10.07, $p<.001$). This effect was significantly stronger in Older Children and Adults than in Younger Children (*p*’s<.001). Examining age contrasts by horizon (Table 5), Older Children and Adults showed similar levels of exploration within Long Horizons ($p=.352$) and within Short Horizons ($p=0.989$), while Younger Children explored more than Adults and Older Children in Short Horizons (*p’s*<.02, Table 5), and similarly to Older Children ($p=.58$) but marginally more than Adults ($p=.05$) in Long Horizons. Thus, Older Children and Adults adapted exploration to time horizons by exploring less under Short Horizons, whereas Younger Children maintained relatively higher levels of exploration and therefore adapted less (Figure 3). Adaptive exploration scores increased across age groups, $F(2,126)=17.71$ (Table S3), $p<.001$, and interacted significantly with age to predict rewards gained, $F(2,123)=6.63$, $p=.002$ (Table S4). Younger Children and Adults who adapted more to time horizons gained significantly more rewards than their less-adaptive peers (t=4.67, $p<.001$, and t=2.19, $p=.03$, respectively). Older Children did not exhibit this relationship ($p=.42$), likely due to their high overall levels of adaptive exploration (Figure 4).

We further examined choice patterns in Long Horizons to assess how participants collected rewards after their initial choices (Supplementary S3). In the Long Horizons trials where Younger Children explored on the first choice (58% of Long Horizons trials), children then consistently choose the largest paint splash on 21% of these trials. On 24% of these trials, they sampled some of the remaining options, and on 55% of these trials, they sampled each of the other available options. In contrast, of the Long Horizons trials where Older Children (65%) and Adults explored first (51%), most were followed by selection of the largest reward option in subsequent choices (Older Children=89% and Adults=86%). Thus, in the majority of Long Horizons trials that started with an Explore choice, older age groups used that information to guide later choices in a reward-maximizing manner, while Younger Children did not.

Testing and Controlling for Effects of Exploit Reward-Size

Given the larger possible rewards from Exploit options across the task, we examined the extent to which the visible exploit reward influenced initial choices. A mixed effects logistic regression predicting Explore initial choices with exploit reward-size showed that larger exploit reward-sizes on a trial predicted lower odds of exploring on that trial (OR=0.285, 95%CI [0.436, 0.515], $z=-17.7$, $p<.001$; Figure 5, Table S5). Further, the magnitude of this exploit reward-size effect differed across age groups, $\chi^2(2)=39.05$, $p<.001$ (Figure 6): Older Children and Adults showed a significantly stronger effect (Older Children: Est=−1.128, SE=0.088, Adults: Est=−0.822, SE=0.071) than Younger Children (Younger Children: Est=−0.423, SE=0.073, age contrasts p's≤.002), and Older Children showed a stronger effect than Adults ($p=.02$). As a result, Younger Children sometimes received *more* rewards than Older Children and Adults, for example, on the trial with the largest reward of the task, which could only be accessed by picking the explore option: 47.5% of Younger Children obtained this maximal reward compared to 7.5% of Older Children and 12.5% of Adults. The exploit reward-size effect did not differ significantly across horizons ($p=.09$) and the three-way Horizons X Age X Reward-Size effect was also insignificant ($p=0.63$).

Given the effect of the size of the Exploit option on initial choices, we statistically controlled for the exploit reward-size X Age interaction in our main model to verify whether differences in exploration were driven by visible reward-driven factors. Controlling for the exploit reward-size X Age effect, the Horizons x Age interaction remained significant, as did the Long vs. Short Horizons contrasts in Adults ($p<.0001$) and in Older Children ($p<.0001$), but not in Younger Children ($p=.084$), reflecting the weaker effect in this age group (Tables 3–5). These findings suggest that age differences in adaptive exploration exist beyond visible reward-driven factors. Further, we reasoned that adaptive exploration (exploring more in Long than Short Horizons) could not have been driven by participants learning about differences in reward associated with the explore and exploit options, because the exploit option provided the largest reward in 5/6 Long Horizons trials compared to 4/6 Short Horizons trials. Thus, if differences in reward had driven differences in exploration, participants would have explored more in short horizons than in long horizons, rather than the reverse.

Choices under Ambiguous Horizons

Next, we examined how ambiguous horizons influenced initial choices across age groups. In the main model, we examined the Ambiguous vs. other horizons contrasts by age group (Table 4). Older Children and Adults explored in Ambiguous Horizons at a level intermediate between Short and Long Horizons (*p's*<.01). Younger Children did not differ in their explore levels in Short and Ambiguous Horizons ($p=0.997$) but explored less in Ambiguous compared to Long Horizons ($p=0.002$). These effects remained significant controlling for the size of the exploit option X age effect (all *p's*<.02).

Considering age contrasts within Ambiguous horizons (Table 5), the preference to explore in Ambiguous horizons differed between Younger Children and older age groups (*p*'s<.02). Adults and Older Children preferred exploiting over exploring under Ambiguous horizons (Adults OR=0.247, 95%CI [0.142, 0.429]; Older Children OR=0.380, 95%CI [0.212, 0.680], *p*'s<.01), but Younger Children did not (OR=1.267, 95%CI [0.684, 2.351], *p*=.45; Table 3, Figure 7). These age group differences remained significant controlling for the exploit-reward size X Age effect, *p's*<0.01, suggesting that age differences exist beyond visible reward-driven factors.

Discussion

This study examined adaptations in explore-exploit decisions to time horizons across development. Previous work suggested that adaptive behavior is evident in early adolescence but continues to improve until at least early adulthood (Somerville et al., 2017). However, the present findings suggest that in a simplified environment, adult-levels of adaptation are evident by ages 11–12 years. Further, 5–6 year-old children showed some evidence of adapting, although significantly less than older children and adults. We also replicated prior findings of adaptations to time horizons in adults.

Although 5–6 year-old children did not show significant adaptation to time horizons after controlling for reward-driven factors, many of these younger children did adapt. These variations in adaptation in a small sample may have contributed to a weaker effect size not quite reaching significance. Thus, although 5–6 year-olds did not adapt as a group, this age may nonetheless be a development window when adaptation to time horizons is emerging. Future work testing larger samples across 4–7 years of age may be particularly informative for examining the emergence of adaptation to time horizons.

Many 5–6 year olds failed to adapt to time horizons because they explored more than older age groups. These results add to growing evidence that when young children face the explore-exploit dilemma, exploration dominates. From an adaptive lens, this early exploratory tendency enables young children to maximize learning and experiences. In our study, the largest reward in the Simplified Horizons Task was discovered by more 5–6 year-olds than by older age groups. This aligns with previous studies that found that through exploration, children discover information that adults miss (Liquin & Gopnik, 2022; Sumner et al., 2019). While an exploratory strategy does not maximize overall reward, it can lead to the discovery of rare outcomes and support children's learning about their environment. More broadly, our findings align with frameworks that emphasize ways in which apparent limitations in cognitive processes and actions early in development can actually support effective learning (Newport, 1990; Smith et al., 2018; Thompson-Schill et al., 2009; Werchan & Amso, 2017).

Although younger children sometimes revealed useful information during exploration in long horizons, they did not always effectively use that information to guide later choices. While on some trials, younger children who explored first in long horizons went on to then consistently choose the largest paint splash, on the majority of trials, younger children went on to sample each of the three remaining options regardless of their reward sizes. This tendency to sample widely and thoroughly is similar to children's behaviors in other search paradigms (Sumner et al., 2019), which appears to maximize information over reward. In the current study, even though children had perfect information after exploring once, many still preferred to sample the remaining, unsampled options, even though no new information was obtained. This behavioral pattern suggests that children were not only driven to obtain information, but also wanted to engage with all options in the environment. Perhaps this reflects a preference for novelty that is dissociable from information and robust across age groups (Cockburn et al., 2022;.Nussenbaum et al., 2022; Wittman et al., 2008).

Adaptive exploration increased with age, with older children and adults showing more exploitation in short and ambiguous horizons. This aligns with previous findings showing that older children made more exploitation decisions than younger children in a reward-gathering search board task (Meder et al., 2021) and seemed more sensitive to future uncertainty (Lagattuta & Sayfan, 2011). What happens across childhood to support this shift? We consider three potential mechanisms. One is developments in children's inhibitory control (Macdonald et al., 2014; Ordaz et al., 2013; Williams et al., 1999). The widespread finding that young children are highly exploratory suggests that this exploratory drive may be a habitual and prepotent behavior. Children may need to engage inhibitory control to overcome a prepotency to explore. Further, to determine whether and when to inhibit exploration, children must use information about horizons to compute the expected value of exploration versus exploitation. This computation is non-trivial (Levin et al., 2007; Weller et al., 2007) and requires the maintenance of more abstract goal representations, a flexibility that develops across childhood and into adulthood (Bunge & Zelazo, 2006; Chevalier & Blaye, 2009; Munakata et al., 2012; O'Donnell et al., 2017). If exploration is a prepotent response in younger children, then we may expect them to show faster decision times to explore compared to exploit decisions. We were unable to test this in the current study because reaction time data was not collected in the Simplified Horizons Task. Future work should examine decision times during explore-exploit decision making, to examine the hypothesis that exploration may be a prepotent response in children.

Second, changes in what constitutes exploration across development might support the emergence of new, reward-maximizing strategies. As a young child explores by uncovering paint cans in the Simplified Horizons Task, their interest in this concrete and simple form of exploration eventually decreases. This decrease can make room for discovery of more abstract forms of exploration, such as new search strategies, which may enable children's eventual discovery of optimal strategies (Mata et al., 2011; Rieskamp & Otto, 2006; Siegler, 1999). Older age groups, however, arrive at the task with years of experience making various explore-exploit decisions, on computers and in other contexts, and can more quickly progress to settling on a preferred strategy. This process of increasingly more abstract forms of exploration might parallel the way that children's cognitive control becomes increasingly abstract, flexible, and self-directed across development (Munakata et al., 2012). Future work should explore how exploration expands in flexibility over time and takes on different forms across development.

Finally, better accuracy in assigning value to external rewards and computing uncertainty across development (Nussenbaum & Hartley, 2019; Baer & Kidd, 2022) may support adaptation to time horizons. In the Simplified Horizons Task, younger children did not adapt readily to time horizons, but did enlist a reward-comparison strategy by exploiting more when the available rewards were larger. This suggests that younger children assigned some value to visible, non-exploratory rewards but did so with more noise than older age groups. Further, improvements in computing uncertainty under more complex environments might also support adaptive exploration. In previous work using the original Horizons Task, where the uncertainty computation was complex, 12-year-olds showed immature levels of adaptation, but in the Simplified Horizons Task, 11–12 year-olds performed similarly to adults. These findings suggest that improvements in value assignment and uncertainty computation across development may support adaptive decision-making across childhood.

The current findings highlight the importance of administering age-adapted measures for examining the emergence of adaptive decision-making and other cognitive processes in children. Previous work has concluded that young children display an exploratory drive, value information over reward, and are poor at tempering their exploration even when it holds little future value (Blanco & Sloutsky, 2021; Sumner et al., 2019). However, even young children engaged in some adaptive decision-making on a Simplified Horizons Task. While the original Horizons Task was suitable for adults and older adolescents and can tease apart different forms of exploration (Meder et al., 2021; Wilson et al., 2014), it is likely too complex for children to capture their nascent adaptive abilities. By using a simplified task, we revealed that older children and some younger children show sensitivity to the reduced value of exploration when time horizons are short and exploited rather than explored to maximize long-term gain.

Understanding how and when a sensitivity to time horizons emerges can shed light on the factors that shape adaptive behavior across development. We contribute to this endeavor by showing earlier emergence of and developmental changes in adaptation to time horizons. This better understanding can inform interventions to support children's developing adaptive behaviors. Indeed, evidence from episodic future thinking interventions--which may act via lengthening time horizons--has shown promise in promoting healthy behaviors (Daniel et al., 2015). If the ability to adapt to time horizons mediates this effect, it is important to understand when and how a sensitivity to time horizons arises. Such advances will enable the creation of interventions best targeted to support self-regulation across development.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Public significance statement:

The more time we have to do something, the better it is to explore different options to learn the best one. This ability to adapt exploration to time horizons may begin to emerge around 5–6 years and reach adult levels by 11–12 years. As children grow older, they explore less and exploit known options more, and this shift might lead to better decision-making at the expense of learning.

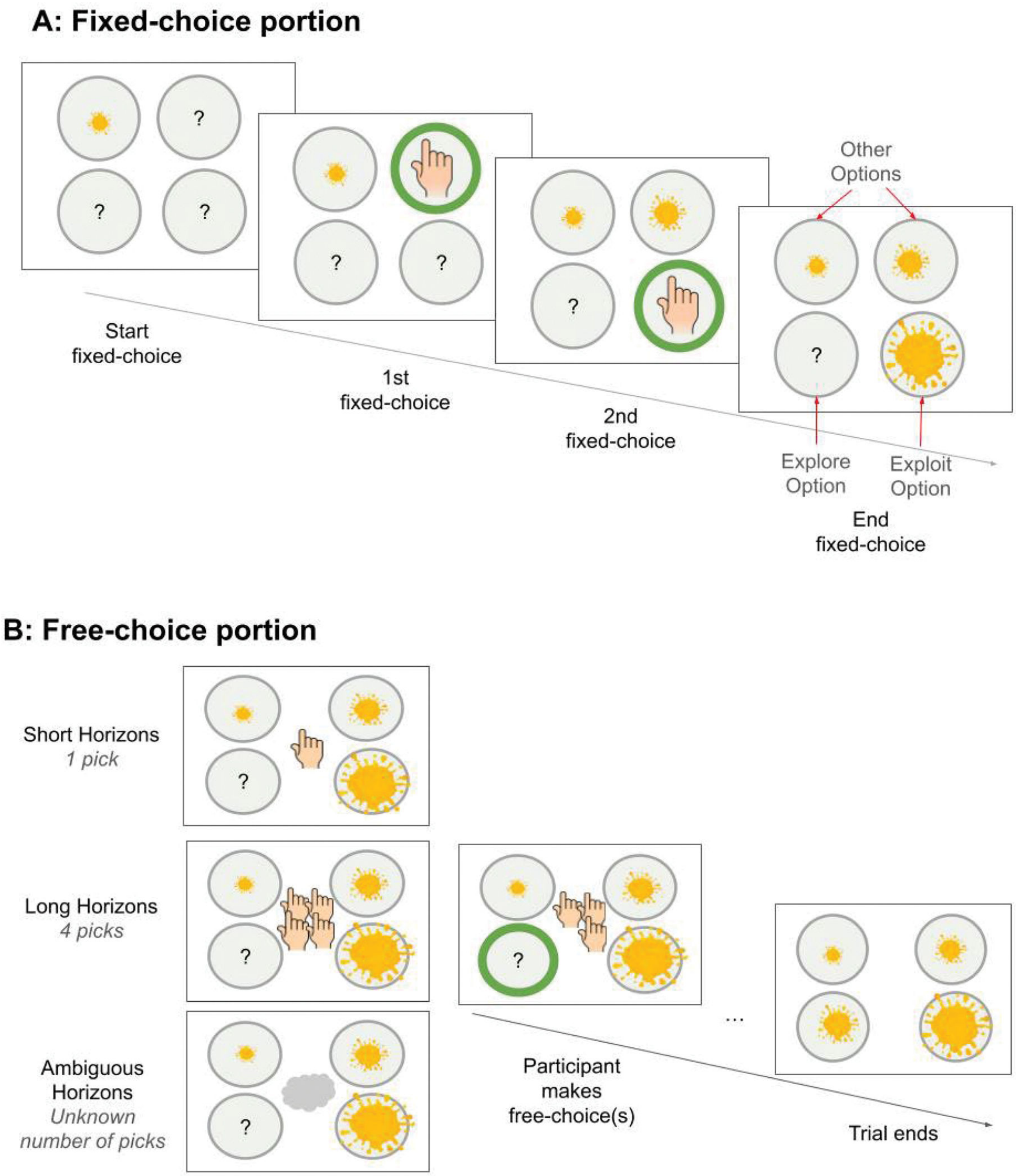

Figure 1. The Simplified Horizons Task

Note. Each practice and test trial began with two fixed-choices (A) followed by a free-choice portion (B). The number of free-choices varied by horizon condition and was indicated by the number of hands: Short= 1free-choice, Long = 4 free-choices, Ambiguous= 50% 1 free-choice and 50% 4 free-choices). For example, in the free-choice portion of a Short horizonstrial (B), asingle hand indicates one free-choice; once the participant makestheir initial free-choice, the trial ends. Hand image icon from “Icon of hand pointer”, FreeSVG.org (https://freesvg.org/hand-pointer). In the publicdomain.

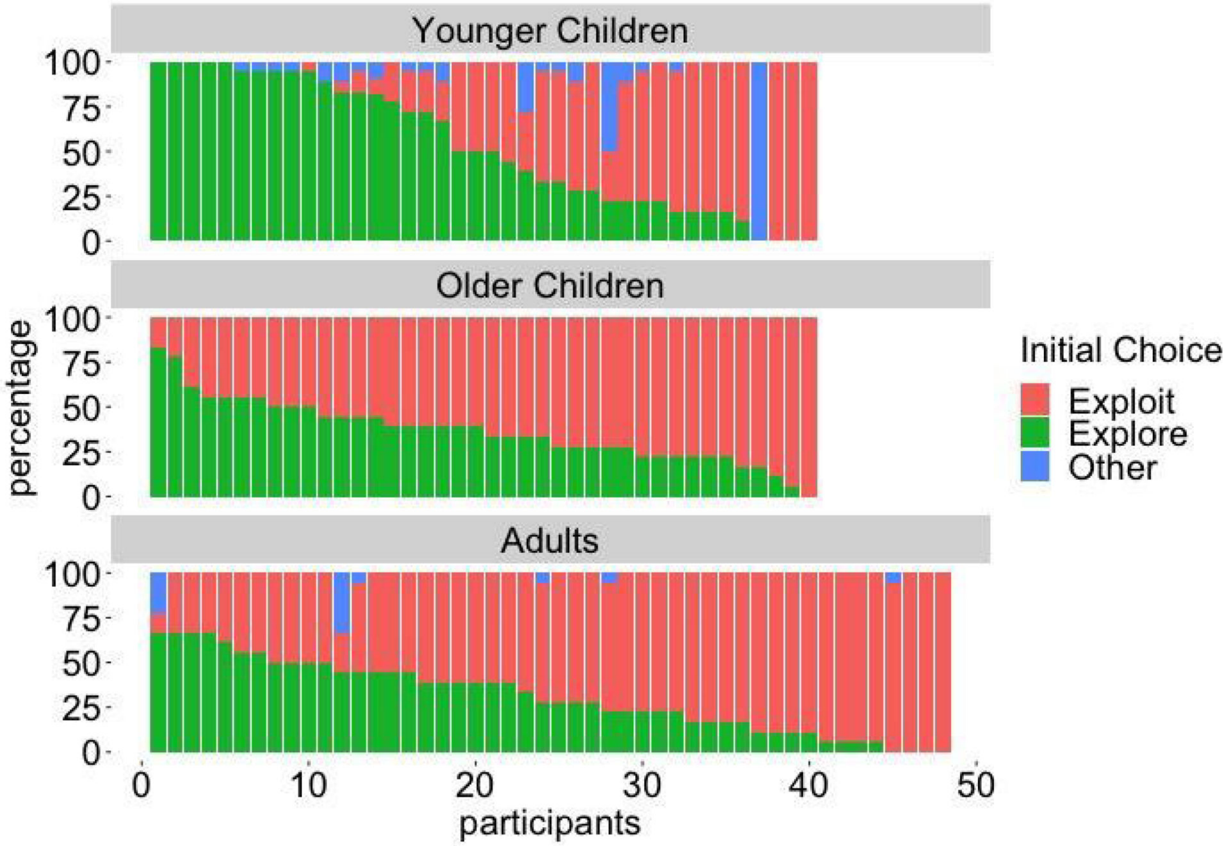

Figure 2. Overall Levels of Explore, Exploit, and Other Initial Choices across Age Groups

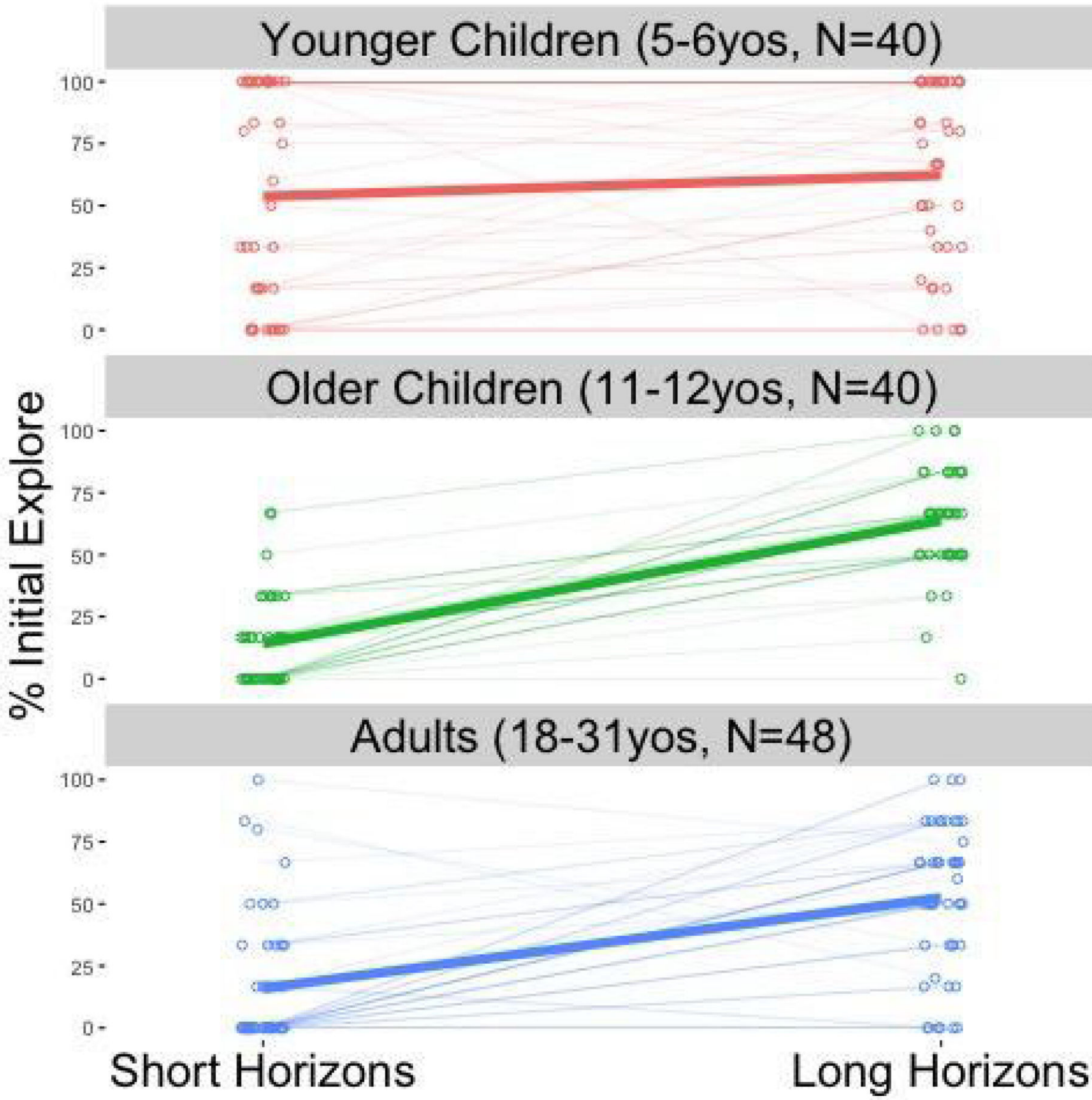

Figure 3. Initial Choices to Explore (by picking an unknown reward) under Short and Long horizons across Age Groups

Note. Adaptive exploration (exploring more under Long Horizons than Short Horizons) increased with age. Older children and adults explored more when horizons were Long than Short (*p's*<.001), while younger children explored similarly across the two horizons (*p*=.084).

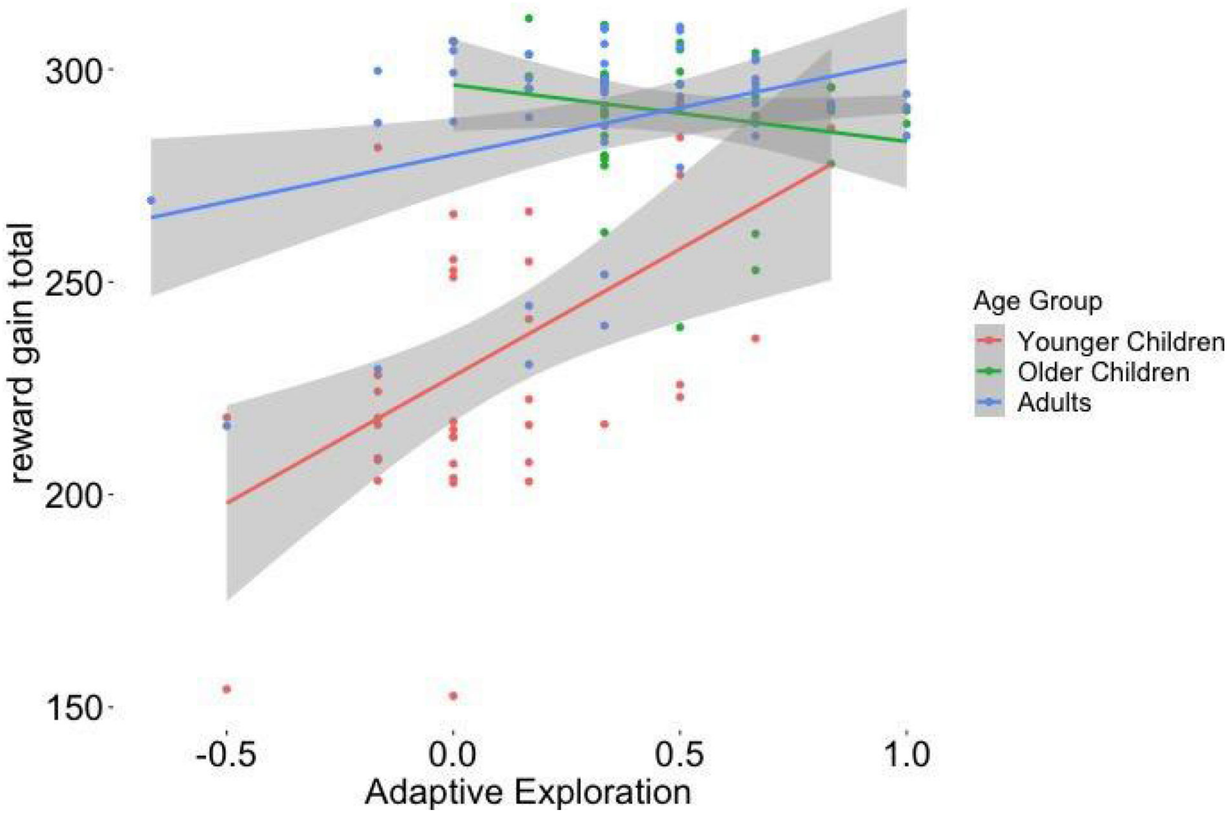

Figure 4. Adaptive Exploration and Total Reward Gained across Age Groups

Note. Younger Children and Adults who adapted more to time horizons gained significantly more total rewards compared with their same-age, less adaptive peers (p's<.05). Older Children did not show this relationship (p=.40), likely due to ceiling effects.

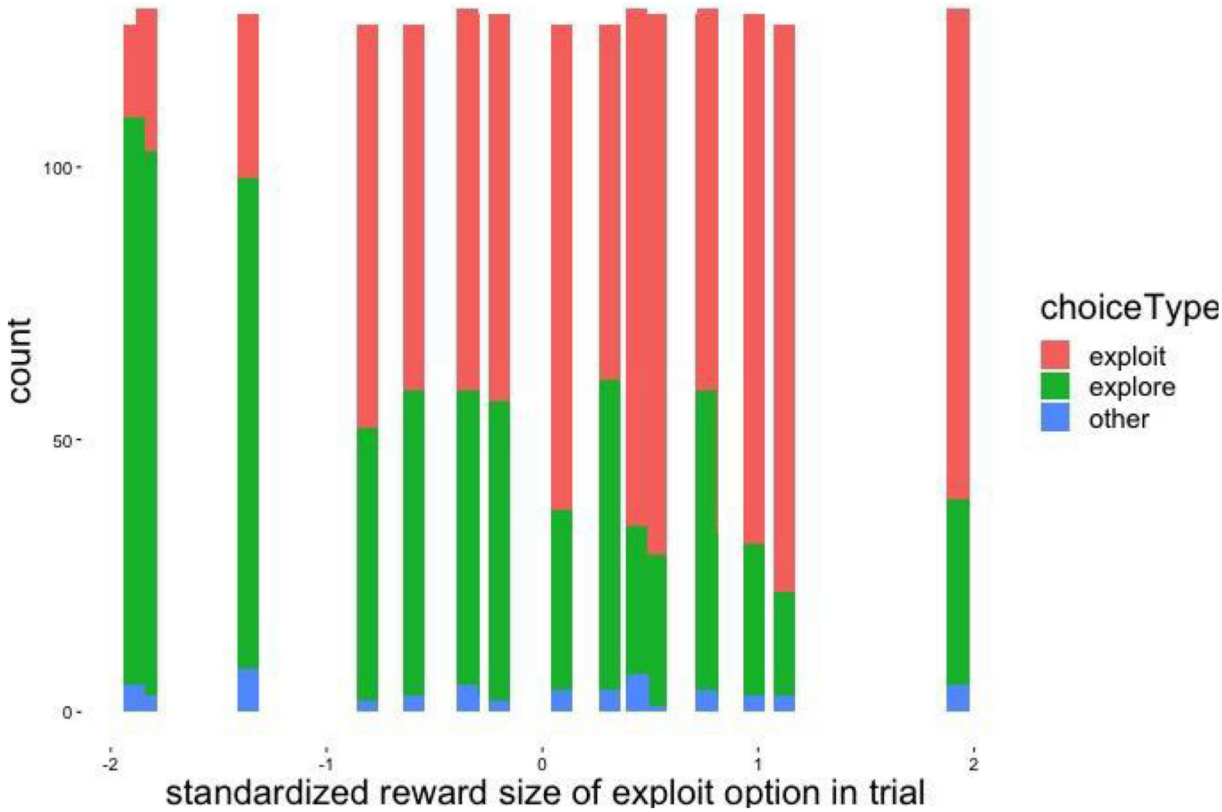

Figure 5. Initial Choices as a Function of Exploit Reward Size

Note. Larger reward sizes of the exploit option on a trial predicted lower odds of exploring on that trial, $p<.001$.

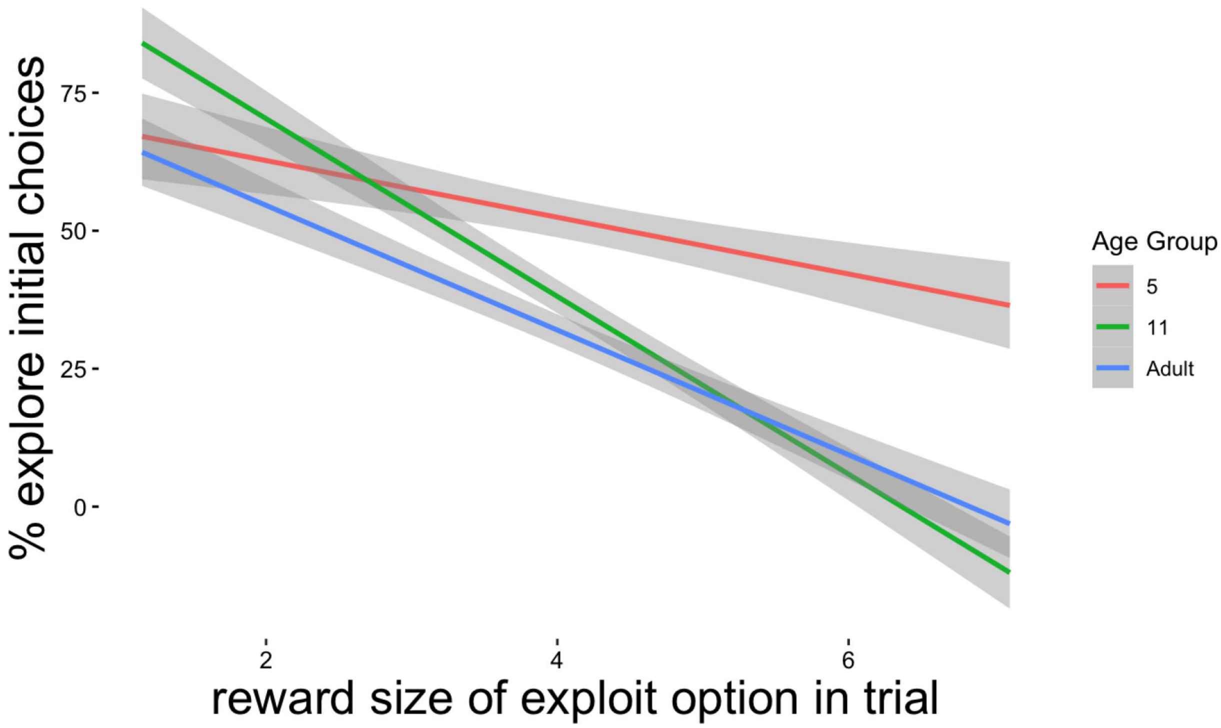

Figure 6. Exploit Reward Size Effect across Age Groups

Note. The effect of the visible exploit reward-size on initial choices differed across age groups, $\chi\chi2(2)=39.05$, $p<.001$: Older Children and Adults showed a significantly stronger effect than Younger Children did (p's<.001), and Older Children showed a stronger effect than Adults ($p=.02$).

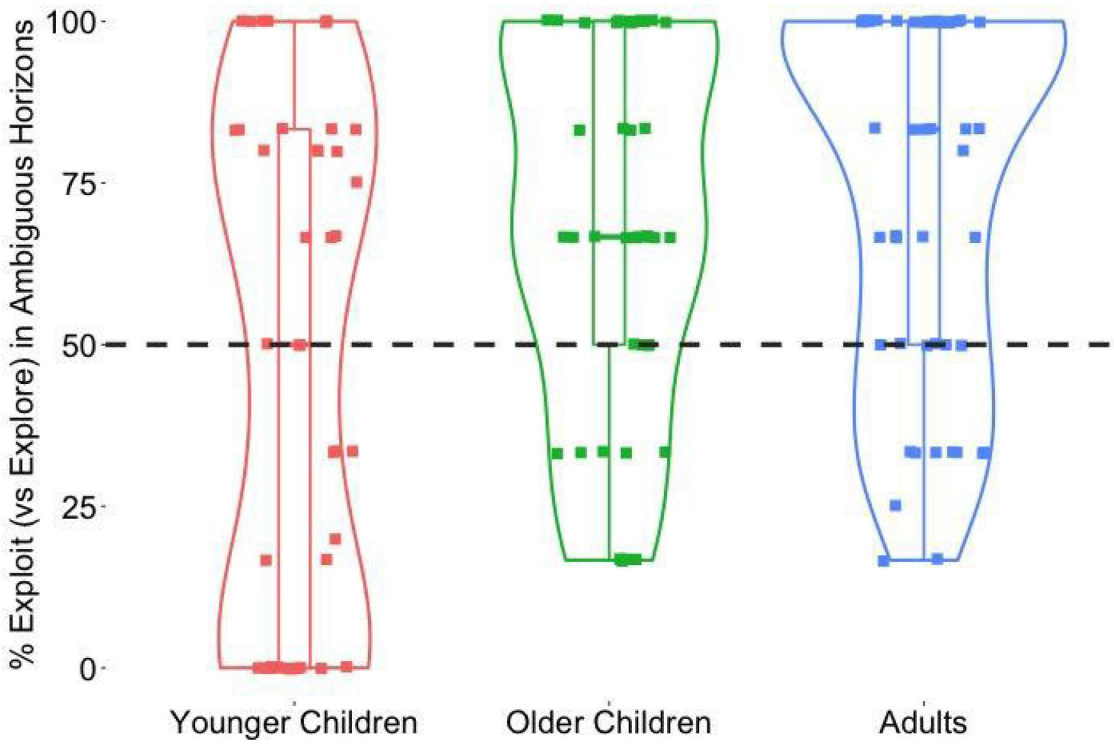

Figure 7. Proportion of Exploit vs. Explore Initial Choices under Ambiguous Horizons across Age Groups

Note. Dotted line = equal preference to explore and exploit. The lower and upper hinges of the box plots correspond to the first and third quartiles (the 25th and 75th percentiles), or the IQR (interquartile range). The upper and lower whiskers extend to the largest values no further than 1.5 * IQR from the corresponding hinge. Older children and Adults preferred to exploit rather than explore under Ambiguous Horizons (*p*'s<.01), whereas Younger Children did not (*p*=.45).

Table 1

Means, standard deviations, and correlations in Younger Children, Older Children, and Adults

Variable	M	SD	1	2	3	4	5	6
Younger Children (N=40)								
1 Age in years	5.46	0.3						
2 % initial choice Explore	51.72	36.15	−.32*					
3 % initial choice Exploit	39.9	35.34	0.21	−.87**				
4 % initial choice Other	8.38	18.05	0.24	−0.29	−0.21			
5 Reward Gained in pixels sq	231.14	39.64	0.15	−.38*	.65**	−.52**		
6 Adaptive Exploration	0.1	0.3	0.19	−0.19	.33*	−0.26	.47**	
Older Children (N=40)								
1 Age in years	11.5	0.28						
2 % initial choice Explore	36.53	17.65	0.16					
3 % initial choice Exploit	63.47	17.65	−0.16	−1.00**				
4 % initial choice Other	0	0	NA	NA	NA			
5 Reward Gained in pixels sq	289.74	14.94	0.04	−0.26	0.26	NA		
6 Adaptive Exploration	0.5	0.24	0.31	0.08	−0.08	NA	−0.22	
Adults (N=48)								
1 Age in years	19.37	2.38						
2 % initial choice Explore	30.9	20.21	−0.16					
3 % initial choice Exploit	67.48	22.1	0.11	−.97**				
4 % initial choice Other	1.62	5.84	0.12	0.2	−.44**			
5 Reward Gained in pixels sq	287.97	22.16	0	−.39**	.53**	−.66**		
6 Adaptive Exploration	0.36	0.36	−0.17	0.21	−0.07	−.48**	.36*	

Note. % initial choice reflects average across all horizons.

* indicates $p < .05$.

** indicates $p < .01$.

Table 2

Mixed logistic regression predicting Explore over Exploit initial choices in all Horizons

Model	Formula	npar	AIC	BIC	logLik	deviance	Chisq	df	Pr(>Chisq)
Base model	Explore ~ 1	2	2571.6	2583	−1284	2567.6			
Model 1	Explore ~ Horizons	4	2304	2326.8	−1148	2296	271.59	2	< .001 ***
Model 2	Explore ~ Horizons + Age	6	2288.1	2322.4	−1138	2276.1	19.871	2	< .001 ***
Main Model	Explore ~ Horizons X Age	10	2263.8	2320.9	−1122	2243.8	32.332	4	< .001 ***

Note. Total subjects = 128, total trials = 2225 (all Horizons, Other choices excluded). The outcome variable, *Explore,* is binary with 1 == trials where the explore option was picked. The predictor variables, *Age* (Younger Children, Older Children, and Adults) and *Horizons* (Long, Short, and Ambiguous), were dummy coded. Predictors were modeled as fixed effects and intercepts were modeled as randomly varying across individuals. Model comparisons were conducted sequentially. Abbreviations: npar= number of parameters, AIC= Aiyake's Information Criterion, BIC= Bayesian information criterion, logLik= log likelihood.

* indicates p < .05.

** indicates p < .01.

*** indicates p < .001.

Table 3

Estimated means by age group and horizons (from Main Model)

				95% CI (in odds)[a]				*Controlling for age X reward-size*			
	Est (logit)	**SE**	**Est (odds)**	**Lower**	**Upper**	**z**	**Pr(>|z|)[b]**	**Est (logit)**	**SE**	**z**	**Pr(>|z|)[b]**
					Younger Children						
Ambiguous	0.237	0.315	1.267	0.684	2.351	0.754	0.451	0.330	0.375	0.880	0.379
Short	0.256	0.316	1.292	0.695	2.401	0.810	0.418	0.498	0.378	1.320	0.187
Long	1.135	0.323	3.111	1.654	5.859	3.517	<.0001 ***	1.092	0.382	2.855	0.004 **
					Older Children						
Ambiguous	−0.968	0.297	0.380	0.212	0.680	−3.254	0.001 ***	−1.196	0.364	−3.282	0.001 **
Short	−2.205	0.327	0.110	0.058	0.209	−6.743	<.0001 ***	−2 271	0.393	−5.778	<.0001 ***
Long	0.697	0.295	2.008	1.125	3.579	2.361	0.018 *	0.646	0.379	1.703	0.089
					Adults						
Ambiguous	−1.398	0.281	0.247	0.142	0.429	−4.974	<.0001 ***	−1.596	0.340	−4.702	<.0001 ***
Short	−2.268	0.301	0.104	0.057	0.187	−7.538	<.0001 ***	−2.319	0.357	−6.494	<.0001 ***
Long	0.144	0.272	1.155	0.678	1.966	0.530	0.596	−0.206	0.334	−0.619	0.536

Note. Estimates reflect odds or logodds (logit) of exploring over exploiting.

[a] Confidence intervals were calculated using Wald’s method.

[b] P-values were Tukey-adjusted for multiple comparisons within each group of 3 tests. Abbreviations: Est= Estimate, SE= standard error, CI= confidence interval.

* indicates p < .05.

** indicates p < .01.

*** indicates p < .001.

Table 4

Horizons contrasts by age group (from Main Model)

				95% CI (in odds)[a]				*Controlling for age X exploit reward-size*			
	Est (logit)	**SE**	**Est (odds)**	**Lower**	**Upper**	**z**	**Pr(>|z|)[b]**	**Est (logit)**	**SE**	**z**	**Pr(>|z|)[b]**
				Younger Children							
Ambiguous vs. Short	0.019	0.252	1.019	0.598	1.610	0.074	0.997	0.168	0.266	0.632	0.803
Ambiguous vs. Long	0.898	0.260	2.454	1.475	4.084	3.455	0.002 **	0.762	0.276	2.756	0.016 **
Short vs. Long	0.879	0.259	2.409	1.450	4.002	3.393	0.002 **	0.594	0.279	2.129	0.084
				Older Children							
Ambiguous vs. Short	−1.237	0.253	0.290	0.177	0.477	−4.882	<.0001 ***	−1.075	0.281	−3.828	0.000 ***
Ambiguous vs. Long	1.665	0.220	5.284	3.435	8.127	7.578	<.0001 ***	1.842	0.286	6.437	<.0001 ***
Short vs. Long	2.902	0.262	18.205	10.899	30.412	11.084	<.0001 ***	2.917	0.323	9.036	<.0001 ***
				Adults							
Ambiguous vs. Short	−0.871	0.236	0.419	0.264	0.665	−3.693	0.001 ***	−0.723	0.251	–2.878	0.011 *
Ambiguous vs. Long	1.542	0.212	4.673	3.083	7.082	7.268	<.0001 ***	1.390	0.240	5.782	<.0001 ***
Short vs. Long	2.412	0.240	11.160	6.978	17.845	10.072	<.0001 ***	2.112	0.267	7.908	<.0001 ***

Note.

[a]Confidence intervals were calculated using Wald's method.

[b]P-values were Tukey-adjusted for multiple comparisons within each group of 3 tests. Abbreviations: Est= Estimate, SE= standard error, CI= confidence interval.

*indicates p < .05.

**indicates p < .01.

***indicates p < .001.

Table 5

Age contrasts by Horizons (from Main Model)

			95% CI (in odds)[a]					*Controlling for age X reward-size*			
	Est (logit)	SE	Est (odds)	Lower	Upper	z	Pr(>|z|)[b]	Est (logit)	SE	z	Pr(>|z|)[b]
					Ambiguous Horizons						
Younger Children vs. Older Children	1.205	0.433	3.338	1.427	7.807	2.781	0.015 *	1.526	0.523	2.915	0.010 **
Younger Children vs. Adults	1.635	0.423	5.130	2.240	11.751	3.868	<.0001 ***	1.926	0.507	3.801	<.0001 ***
Older Children vs. Adults	0.430	0.409	1.537	0.690	3.424	1.052	0.544	0.400	0.496	0.806	0.699
					Short Horizons						
Younger Children vs. Older Children	2.461	0.456	11.719	4.798	28.623	5.402	<.0001 ***	2.769	0.546	5.069	<.0001 ***
Younger Children vs. Adults	2.525	0.438	12.485	5.293	29.443	5.767	<.0001 ***	2.817	0.521	5.404	<.0001 ***
Older Children vs. Adults	0.063	0.443	1.065	0.447	2.539	0.143	0.989	0.048	0.529	0.090	0.996
					Long Horizons						
Younger Children vs. Older Children	0.439	0.437	1.551	0.658	3.652	1.003	0.575	0.446	0.538	0.829	0.685
Younger Children vs. Adults	0.991	0.422	2.695	1.178	6.164	2.348	0.049 *	1.298	0.508	2.555	0.029 *
Older Children vs. Adults	0.553	0.401	1.738	0.792	3.814	1.378	0.352	0.852	0.505	1.687	0.210

Note.

[a]Confidence intervals were calculated using Wald's method.

[b]P-values were Tukey-adjusted for multiple comparisons within each group of 3 tests. Abbreviations: Est= Estimate, SE= standard error, CI= confidence interval.

[*] indicates p < .05.

[**] indicates p < .01.

[***] indicates p < .001.