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Brief Report

Age differences in intertemporal choice among children, adolescents, and adults



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ABSTRACT

When choosing between sooner–smaller and later–larger rewards (i.e., intertemporal choices), adults typically prefer later–larger rewards more often than children. Intertemporal choice preferences have been implicated in various impulsivity-related psychopathologies, making it important to understand the underlying mechanisms not only in terms of how reward magnitude and delay affect choice but also in terms of how these mechanisms develop across age. We administered an intertemporal choice paradigm to 60 children (8–11 years), 79 adolescents (14–16 years), and 60 young adults (18–23 years). The paradigm systematically varied amounts and delays of the available rewards, allowing us to identify mechanisms underlying age-related differences in patience. Compared with young adults, both children and adolescents made fewer later–larger choices. In terms of underlying mechanisms, variation in delays, absolute reward magnitudes, and relative amount differences affected choice in each age group, indicating that children showed sensitivity to the same choice-relevant factors as young adults. Sensitivity to both absolute reward magnitude and relative amount differences showed a further monotonic age-related increase, whereas no change in delay sensitivity occurred. Lastly, adolescents and young adults weakly

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displayed a *present bias* (i.e., overvaluing immediate vs. future rewards; nonsignificant and trend, respectively), whereas children showed a nonsignificant but opposite pattern, possibly indicating that specifically dealing with future rewards changed with age. These findings shed light on the underlying mechanisms that contribute to the development of patience. By decomposing overt choices, our results suggest that the age-related increase in patience may be driven specifically by stronger sensitivity to amount differences with age.

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Introduction

At any age, people encounter choices between sooner–smaller (SS) and later–larger (LL) rewards. For example, the decision to eat a high-calorie donut now versus experiencing better health later. Whereas adults typically might be expected to understand that the delayed LL reward is ultimately superior to the immediately available SS reward, children might exhibit more shortsightedness and choose the SS reward instead. Indeed, cross-sectional studies have shown that with increasing age more LL rewards are chosen (e.g., [Prencipe et al., 2011](#)). Given that intertemporal choice preferences show reliable associations with various (developmental) impulsivity-related psychopathologies and problem behaviors (e.g., [Amlung et al., 2019](#); [Lempert et al., 2019](#)), it is relevant to advance understanding of not only its underlying mechanisms but also how these mechanisms might change across age. Understanding, recognizing, and predicting the antecedents of such problematic behaviors from a young age onward might result in more efficient decision aids and intervention or prevention efforts (e.g., focusing on different aspects depending on age).

Intertemporal choice paradigms assess delay discounting, which refers to the decrease in value of an option when the delay to its receipt increases ([Samuelson, 1937](#)). Individuals differ in the extent to which rewards lose value over time, called the discount rate. Steeper discount rates are an index of both impulsiveness and impatience ([Takahashi, 2009](#)). Most cross-sectional studies using intertemporal choice paradigms found that children discount rewards more steeply than adolescents and adults (e.g., [Olson et al., 2007](#), [Prencipe et al., 2011](#); but see [Demurie et al., 2012](#)) and adolescents discount rewards more steeply than adults (e.g., [de Water et al., 2014](#); [Olson et al., 2007](#); [Ripke et al., 2012](#)), suggesting a monotonic increase in patience with age. Others, however, found an adolescent-emergent pattern, such that discounting decreased until adolescence and then stabilized ([Achterberg et al., 2016](#); [Steinberg et al., 2009](#); [van den Bos et al., 2015](#)).

Developmental processes, such as an increase in future orientation ([Steinberg et al., 2009](#); [van den Bos et al., 2015](#)) and the development of cognitive control ([Achterberg et al., 2016](#); [Steinbeis et al., 2016](#)), have been proposed to explain the age-related decreases in discounting. However, these explanations do not address the level of choice-relevant processes, that is, how age groups might differ in their sensitivity to the amounts or delays of available rewards. A few adolescent-only studies addressed choice-relevant processes and found that more patient choices correlated with stronger relative amount sensitivity and weaker delay sensitivity ([de Water et al., 2017](#); [Mies et al., 2019](#)), which raises the question of whether changes in these processes might also underlie age-related changes in patience. Furthermore, [Laube et al. \(2017, 2020\)](#) investigated whether sensitivity to immediate rewards changed within adolescent boys but found no age-related differences (instead, they found some evidence for testosterone-related differences). Interestingly, an influential neurobiological model of impulsivity, often referred to as the neural imbalance model ([Casey et al., 2008](#); [Steinberg, 2008](#)), posits that during the transitions from childhood to adolescence to adulthood subcortical affective networks mature faster than cortical cognitive control networks. This results in a neural imbalance during adolescence that is thought to drive heightened impulsivity, risk seeking, and reward sensitivity ([Casey et al., 2008](#); [Steinberg, 2008](#)). Based on this theory, we might expect a quadratic

age pattern, such that specifically adolescents would display the most impatient choices and strongest amount sensitivity.

The current study investigated age-related changes in the mechanisms underlying intertemporal choices in typically developing children (8–11 years), adolescents (14–16 years), and young adults (18–23 years) using a cross-sectional design. The intertemporal choice task systematically varied four factors that have been shown to influence intertemporal choice in adults (e.g., [Figner et al., 2010](#); [Foerde et al., 2016](#)). They are therefore relevant candidate mechanisms underlying age-related changes in patience, yet they have not previously been studied across children, adolescents, and young adults. First, we varied the delay length between the SS and LL rewards because longer delays generally lead to less patient choices ([Kirby & Herrnstein, 1995](#); [Mazur, 1987](#)). Second, we varied whether the SS choice was an immediate or future reward because immediate rewards are often overvalued (i.e., leading to less patient choices) compared with when both rewards are future rewards. This is known as the *present bias*, *now effect*, or *immediacy effect* (e.g., [Figner et al., 2010](#); [Prelec & Loewenstein, 1991](#)). Third, we varied the absolute magnitude of SS rewards¹ and, fourth, varied the relative SS/LL amount difference because both larger absolute reward magnitudes and larger relative amount differences generally lead to more patient choice ([Prelec & Loewenstein, 1991](#)).

Based on the age patterns found in previous studies, we expected to find either a monotonic increase in LL choice with age (i.e., children < adolescents < young adults) or an adolescent-emergent pattern (i.e., children < adolescents = young adults). However, based on the neural imbalance model, one might instead expect a quadratic age pattern (i.e., adolescents < children ≈ young adults). Importantly, by including children, adolescents, and young adults, we could distinguish among these three possible age patterns. Furthermore, the use of a decomposable task allowed us to investigate the underlying mechanisms that contribute to the age pattern. It is likely that one or more of the underlying mechanisms would follow a similar (i.e., monotonic, adolescent-emergent, or quadratic) age pattern as the main effect of age, such that the underlying mechanism contributes to the age effect. Specifically, stronger effects of absolute reward magnitude and/or relative amount difference, and weaker effects of delay and/or present bias, would be expected to contribute to more patient choices regardless of which age group showed the most patient choices.

Method

Participants

In total, 60 children (8–11 years; 26 female; $M_{\text{age}} = 10.2$ years), 79 adolescents (14–16 years; 31 female; $M_{\text{age}} = 14.9$ years), and 60 young adults (18–23 years; 22 females; $M_{\text{age}} = 19.8$ years) participated. Children and adolescents were recruited through primary and secondary schools; young adults were second-year university students. All participants provided informed consent (young adults: written; children and adolescents: verbal). For underage participants, primary caretakers were informed about the experiment and provided with the opportunity to exempt their children from participating. The study was approved by the ethics research board of the University of Amsterdam.

All participants received a small gift for participating; the young adults were also given course credit for participation. To make the task incentive compatible, one person in the group (i.e., school or university classes) was randomly selected. For this participant, one randomly selected trial was paid out for real (with real delays when a future reward was chosen and amounts divided by 10).

Procedure

Participants completed two task versions separated by an unrelated task. Instructions were given face to face in pairs (for the children) or in groups of at most 5 participants (for the adolescents and

¹ Note that the effect of increasing absolute reward magnitudes leading to more patient choice is an often-found effect and is typically known as the magnitude effect (e.g., [Prelec & Loewenstein, 1991](#); [Thaler, 1981](#)). However, to the best of our knowledge, it has not been studied across age groups before. To make the amounts more appropriate for children, we used relatively smaller ranges than in the original studies.

young adults). Participants were asked to indicate their true preference and knew that any of their choices could be paid out for real. The task was then demonstrated on the computer by an experimenter. After 4 practice trials, the actual task started. Participants completed the task individually with an experimenter present in the room. Due to time shortage, 12 participants completed only one version of the intertemporal choice task (2 young adults and 10 adolescents). We did not collect any information on IQ or socioeconomic status (SES).

Intertemporal choice task

The intertemporal choice task consisted of 62 trials in total, each offering a choice between a sooner–smaller reward and a later–larger reward. The SS and LL rewards were simultaneously presented on a computer screen, with one option on the left and the other on the right (Fig. 1). The left or right option was chosen by pressing the “q” or “p” key, respectively, after which the next trial started automatically. Response times were also recorded. Position of the SS and LL rewards was counterbalanced across two task versions, whereas the order of trials within each task version was randomized. Lastly, the order in which both task versions were presented was counterbalanced between participants. Data were collected using the “hosted online portal” of Columbia University’s Center for the Decision Sciences, following published security guidelines (Westfall et al., 2012).

The trials represented a design that varied four within-participant variables of interest (see also Figner et al., 2010; Foerde et al., 2016). First, the SS delivery time was either today or in 14 days. Second, the delay between the SS and LL rewards was 3, 14, or 28 days. Third, SS amounts were pseudo-randomly drawn from a distribution with $M = €38$ and range = €16 to €70. Fourth, the LL amount was always 3%, 10%, 20%, 30%, or 50% larger than the SS amount. Lastly, we implemented an overall non-significant delay or acceleration framing manipulation based on reading order and the counterbalanced SS/LL position across the two task versions (delay frame: SS left; acceleration frame: LL left).² All variables except SS amount were varied orthogonally.

The task also included two attention check trials (one per task version) where the LL amount was a “later-but-smaller” reward than the SS amount. Here, participants should always choose the SS reward (children: $n_{\text{total-mistakes}} = 6$; adolescents: $n_{\text{total-mistakes}} = 4$; adults: $n_{\text{total-mistakes}} = 4$). These trials were removed for the analyses.

Analyses

We used mixed-effects models in a Bayesian framework in R (R Core Team, 2018), calculating posterior credible intervals (CIs) using the *brm* function of the R package *brms* (Bürkner, 2017), which provides an interface to Stan (Carpenter et al., 2016). Effects were deemed significant if the corresponding 95% CI did not include 0 and deemed a trend effect when the 90% CI did not include 0. We do not report standardized effect sizes because there is no generally accepted way to calculate them for mixed-effects models due to the way in which variance is partitioned (Rights & Sterba, 2019). To model the repeated measurement structure of the data and avoid inflated Type I errors, we used maximum random-effect structures as recommended by Barr et al. (2013) by including participant-specific random effects.

The dependent variable was choice (SS or LL). As fixed effects, we included age group (children or adolescents or young adults), SS delivery (immediate or in 14 days), delay (continuous), SS amount (continuous), relative amount difference (continuous), and frame (delay or acceleration). We also included all two-way interactions with age group and order of frame (delay or acceleration first; between participants) as main effect to control for possible order effects. Continuous predictors were standardized; categorical predictors were sum-to-zero coded. We conducted planned pairwise age group comparisons using the *emmeans* package (Lenth, 2019) regardless of the omnibus choice model

² We had originally included an additional task factor intended as a subtle delay or acceleration framing manipulation to investigate possible age group differences in this framing effect. However, we found this manipulation to be ineffective across several previous studies and therefore do not discuss it further here (for more details, see Appendix S1 in the supplementary material).

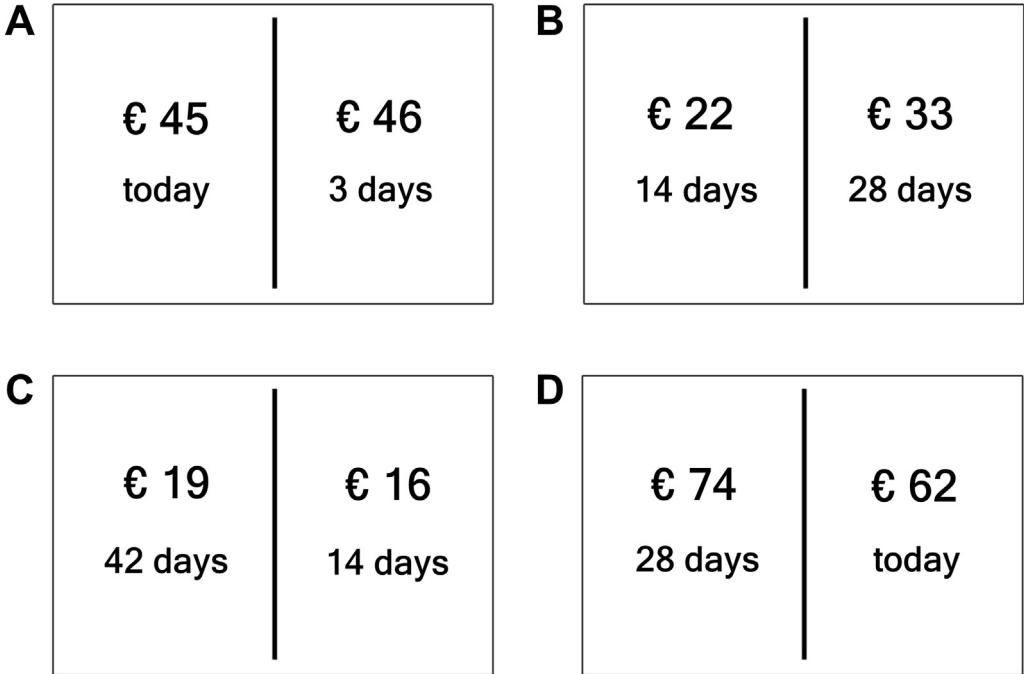


Fig. 1. Overview of task stimuli, with either the sooner–smaller (SS) reward on the left side (acting as delay frame) (A–B) or the later–larger (LL) reward on the left side (acting as acceleration frame) (C–D) using either an immediate SS delivery (A–D) or a future SS delivery (i.e., in 14 days) (B–C). Across trials, the LL delay was 3 days (A), 14 days (B), or 28 days (C–D), whereas also both absolute reward magnitudes and relative (SS or LL) amount differences varied. The real stimuli were in Dutch (available at <https://osf.io/g2yf7>) because the study was run in the Netherlands.

results. Although the specific age-related default contrasts from that model were never of interest to us, running the omnibus model did allow us to extract all pairwise age comparisons of interest (see also Appendix S2 in the online [supplementary material](#)). Furthermore, this approach allowed us to detect each possible (linear or nonlinear) age pattern. Crucially, if at least one of the pairwise age group comparisons was significant, we regarded this as a significant interaction between age group and the respective predictor irrespective of whether a significant effect was found for the default contrasts in the omnibus choice model. For more analysis details (including those from two sets of additional exploratory analyses), see Appendix S2. Data and analysis scripts are available at <https://osf.io/g2yf7>.

Results

Main choice model

For results of the omnibus choice model, see [Table S1](#) in the [supplementary material](#). For task effects per age group and pairwise age comparisons, see [Tables 1 and 2](#), respectively.

Task effects

As expected, delay, relative amount difference, and SS amount showed significant effects, such that more LL choices were made with (a) shorter delays, (b) larger relative SS/LL amount differences, and (c) larger absolute reward magnitudes ([Table S1](#)). Thus, we replicated the typical delay, relative amount difference, and magnitude effects. However, the present bias was not significant ([Table S1](#)),

Table 1Coefficients (B_{EMM} values) and 95% credible intervals per age group (estimated from the omnibus choice model).

Effect	Children (8–11 years)		Adolescents (14–16 years)		Young adults (18–23 years)	
	B_{EMM}	95% CI	B_{EMM}	95% CI	B_{EMM}	95% CI
SS amount (magnitude effect)	0.280*	[0.160, 0.413]	0.640*	[0.522, 0.765]	0.858*	[0.683, 1.016]
Relative amount difference	1.226*	[0.976, 1.509]	1.771*	[1.536, 2.031]	2.712*	[2.368, 3.086]
Delay SS delivery (present bias)	-1.460*	[-1.760, -1.161]	-1.515*	[-1.783, -1.245]	-1.204*	[-1.504, -0.906]
Frame (acceleration or delay)	0.219	[-0.060, 0.488]	-0.209	[-0.456, 0.036]	-0.290 [†]	[-0.536, -0.010]
	0.318	[-0.085, 0.700]	0.114	[-0.260, 0.458]	-0.129	[-0.558, 0.317]

Note. For trend effects, 90% credible intervals (CIs) are reported instead of 95% CIs. SS, sooner–smaller; EMM, estimated marginal means.

*Significant.

[†]Trend.**Table 2**

Pairwise age group differences and 95% credible intervals (estimated from the omnibus choice model).

Effect	Children vs. adolescents		Adolescents vs. young adults		Children vs. young adults	
	Δ_{EMM}	95% CI	Δ_{EMM}	95% CI	Δ_{EMM}	95% CI
Age group	-0.436	[-1.46, 0.438]	-2.248*	[-3.260, -1.340]	-2.687*	[-3.660, -1.723]
SS amount (magnitude effect)	-0.358*	[-0.534, -0.188]	-0.217*	[-0.409, -0.012]	-0.578*	[-0.780, -0.369]
Relative amount difference	-0.544*	[-0.919, -0.202]	-0.944*	[-1.387, -0.550]	-0.485*	[-1.931, -1.069]
Delay SS delivery (present bias)	0.059	[-0.348, 0.450]	-0.311	[-0.713, 0.080]	-0.256	[-0.668, 0.160]
Frame (acceleration or delay)	0.430*	[0.063, 0.799]	0.078	[-0.307, 0.491]	0.508*	[0.090, 0.919]
	0.204	[-0.331, 0.733]	0.249	[-0.330, 0.797]	0.447	[-0.142, 1.015]

Note. For categorical predictors, differences in estimated cell means are compared; for continuous predictors, differences in estimated regression coefficients are compared. CI, credible interval; SS, sooner–smaller; EMM, estimated marginal means.

*Significant.

consistent with Foerde et al. (2016). Thus, on average, participants did not adjust their choice depending on whether the SS reward was immediate or delayed. Lastly, order was not significant, suggesting that no learning or fatigue effects occurred. To summarize, we confirmed the most important task effects.

Age group effects

Pairwise age comparisons showed that the proportion of LL choices was significantly lower in both children and adolescents compared with young adults, whereas children and adolescents did not differ from each other ($M_{\text{children}} = .444$; $M_{\text{adolescents}} = .493$; $M_{\text{adults}} = .660$) (Table 2 and Fig. 2A). Thus, children and adolescents were significantly more impatient compared with young adults, partly replicating previous studies where increases in patience with age have been reported. Furthermore, the effects of absolute reward magnitude and relative amount difference differed significantly among the age groups (Table 2). Although each age group made significantly more LL choices when absolute and relative amount differences increased (Table 1), children exhibited significantly weaker magnitude and relative amount difference effects compared with adolescents and young adults, and adoles-

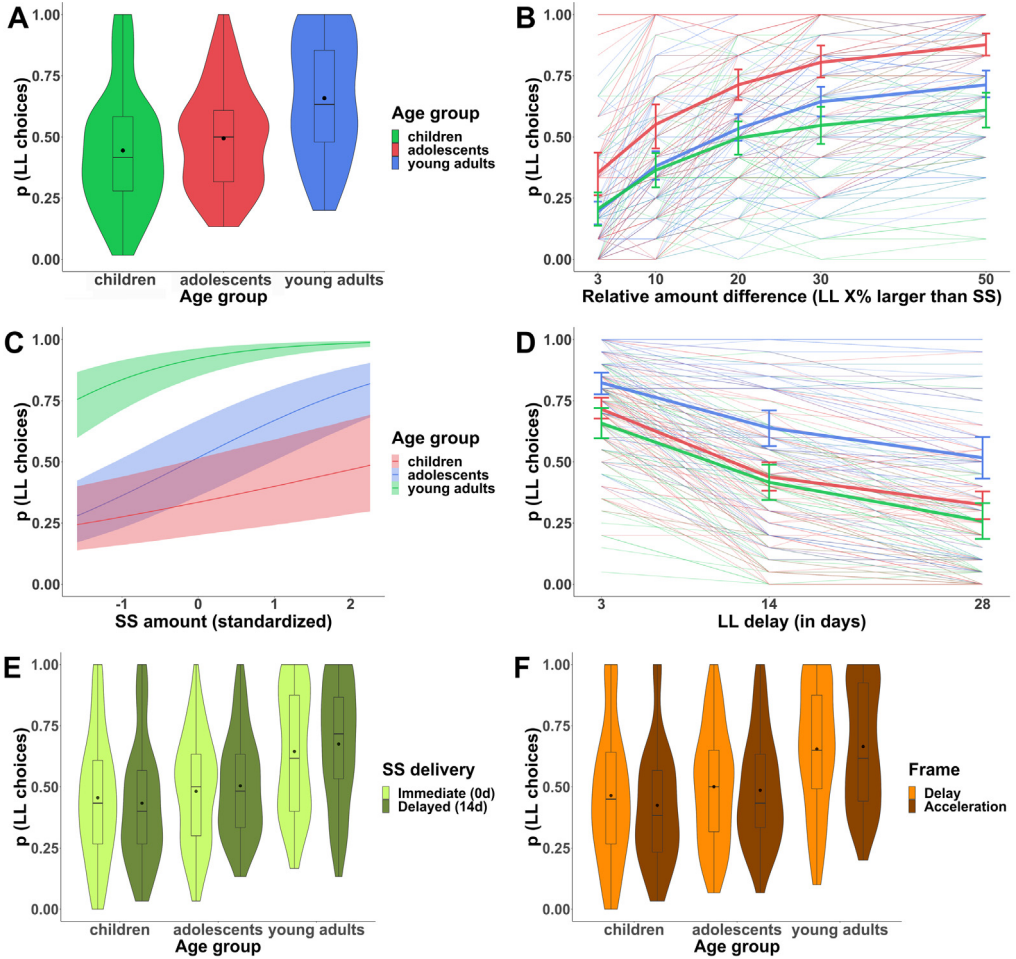


Fig. 2. Overview of all tested age effects on intertemporal choice, with the main effect of age group (A) and significant (B–C) and nonsignificant (D–F) age group differences for all tested underlying mechanisms: (B) relative sooner–smaller or later–larger (SS or LL) amount differences; (C) absolute SS amounts (i.e., the magnitude effect); (D) LL delay; (E) SS delivery (i.e., immediate or in 14 days; the present bias); (F) the overall ineffective delay vs. acceleration framing manipulation (i.e., delay frame: SS left; acceleration frame: LL left). Plots A, E, and F show combined violin and box plots based on the raw data (with black dots representing means). In Plots B and D, the thick lines represent the average effect per age group, whereas the thinner lines represent individual participants based on the raw data. Plot C is the only plot that displays estimated marginal means due to the nonfactorial manipulation of SS amount (all other predictors were varied according to a full-factorial design). Importantly, this means that the effect is displayed while marginalizing over the other predictors. This results in seemingly higher choice proportions compared with the other plots that display raw data. Note further that in Plot E, for adolescents the medians and means show opposite patterns, but statistics are conducted on means. This suggests that, similar to adults, adolescents made somewhat more LL choices during delayed SS delivery than during immediate SS delivery.

cents also showed significantly weaker magnitude and relative difference effects compared with young adults (Fig. 2B and 2C and Table 2).

The present bias also differed significantly among the age groups (Table 2). Although young adults showed a trend for displaying the present bias, it was not significant in children and adolescents (Table 1). More important, whereas the effect was in the expected direction in adolescents and young adults (i.e., more SS choices during immediate SS delivery than during future SS delivery), children

showed an opposite pattern (i.e., more LL choices during immediate SS delivery than during future SS delivery) (Fig. 2E). It is possible that the significantly different patterns in children versus adolescents and young adults explain why the present bias was nonsignificant across the whole sample (Table S1). Interestingly, the delay effect did not differ among the age groups (Table 2), although each age group displayed a significant delay effect (Table 1 and Fig. 2D). This suggests that the way in which children represented delays of 3, 14, and 28 days might not be different from how adolescents and/or young adults represented them.

Lastly, we conducted two different sets of analyses that are reported only in the [supplementary material](#) due to their exploratory nature. First, we explored the presence of age-related differences *within* each age group. For the full results, see Appendix S3, Table S2, and Fig. S1. Second, as secondary measures we estimated, compared, and correlated (a) median response times, (b) choice consistency, and (c) discount rates between and across age groups to provide additional information about underlying choice processes, possible speed–accuracy trade-offs, and changes therein across age groups. For the full results, see Appendix S4, Tables S3 and S4, and Figs. S2 and S3.

Discussion

This cross-sectional study investigated the effects of age on overt intertemporal choice and particularly aimed to define which underlying mechanisms might explain these age differences. Overall, both children and adolescents made less patient choices than young adults. Regarding underlying mechanisms, varying delays, relative reward differences, and absolute reward magnitudes affected choice in the expected directions in each age group. However, sensitivity to both relative and absolute reward magnitudes showed a further monotonic increase with age group, whereas no age-related change in the delay effect occurred. Lastly, the present bias also differed significantly among age groups: Although adolescents and young adults weakly displayed this effect (i.e., nonsignificant and trend), children showed a nonsignificant effect in the opposite direction. Together, these results suggest that specifically age-related increases in amount—but not delay—sensitivity contribute to the typically reported increase in patience with age.

The increased patience in young adults compared with children and adolescents replicates previous research (e.g., [de Water et al., 2014](#); [Prencipe et al., 2011](#); [Ripke et al., 2012](#)). However, unlike most studies, but like [Demurie et al.'s \(2012\)](#) study, we did not find a difference between children and adolescents. In addition, some studies found adolescent-emergent patterns ([Achterberg et al., 2016](#); [Steinberg et al., 2009](#); [van den Bos et al., 2015](#)), whereas we seemed to find an “adult-emergent” pattern, such that young adults made more patient choices compared with both children and adolescents. Note, however, that whereas the young adults were all university students, the adolescents and children came from primary and secondary schools, likely with more variable and on average lower educational levels. Given that educational level is linked to IQ and SES, and both have been found to be associated with more patience (e.g., [Grandin et al., 2022](#); [Wilson et al., 2011](#)), this could have inflated the difference between young adults and children and adolescents. However, this is unlikely to explain why children and adolescents did not differ given that both included more variable educational levels. Thus, although nearly all studies find age-related increases in patience, the precise shape of this increase (monotonic, linear, quadratic, adolescent-emergent, or adult-emergent) likely depends on specific differences in study designs (e.g., the used task, adaptive or nonadaptive discount procedures, continuous or discrete age predictors, included ages or sample sizes).

Most critically, we attempted to shed light on possible underlying mechanisms. Interestingly, children aged 8 to 11 years already showed sensitivity to the same underlying mechanisms as adolescents and young adults (i.e., both amount effects and the delay effect). Indeed, although many studies (including ours) found that children are more impatient, they were not inconsiderately so. Thus, our results suggest that age-related differences in overt intertemporal choice cannot be explained by insensitivity to delays or amounts in children.

Instead, sensitivity to both absolute reward magnitudes and relative amount differences showed a further age-related monotonic increase, such that children showed the least sensitivity to these amount effects and young adults showed the most. These results expand the findings from [de](#)

Water et al. (2017) and Mies et al. (2019), who found that in adolescents more patience was correlated with a stronger relative amount difference effect. We also showed that sensitivity to both relative amount differences and absolute reward magnitudes changes across age groups and that these amount sensitivity changes contribute to the age-related increase in patience: Older individuals not only were more patient but also differentiated more between absolute and relative amount differences compared with younger individuals. If so, one might also expect age-related increases in reward valuation (i.e., based on subjective ratings). Indeed, de Water et al. (2014) found that adults showed higher reward valuation sensitivity than adolescents, yet Steinbeis et al. (2016) found no age-related change—although in a considerably smaller sample of only children (7–13 years). Most interesting, in neither study could reward valuation explain age differences in choice. This may suggest that not (just) the valuation of rewards but specifically how rewards and delays are integrated and compared in a choice context is what changes with age, such that specifically when needing to wait for rewards children somewhat underestimate how much more they get for waiting (compared with adolescents and young adults).

Such an integration process may also explain why the age-related changes in underlying mechanisms (i.e., monotonic increases) did not directly match the age-related changes in overt choice (i.e., an adult-emergent pattern). It is possible that assuming a direct one-to-one link between the mechanisms we studied here and overt choice is too simplistic given that each mechanism may have its own developmental time course (see, e.g., Lee et al., 2013) and ultimately all mechanisms together determine choice. This would suggest that when developing decision aids or intervention or prevention efforts, one might better use an integrative decision-making context than to focus on separate mechanisms in isolation.

Interestingly, we found no adolescent peak in overt impatience, which one might expect based on the neural imbalance model (Casey et al., 2008; Steinberg, 2008). Furthermore, amount sensitivity increased into young adulthood, which seems inconsistent with the proposed heightened sensitivity of the social-affective subcortical network during adolescence. However, given that most studies report monotonic age effects in intertemporal choice, one could argue that such choices might not be affective or engaging enough to trigger an imbalance between the affective and cognitive control systems. Still, developmental neuroimaging studies typically find that both networks are activated during intertemporal choices and that changes in connectivity between the striatum and prefrontal cortex relate to the age-related decrease in impulsive choices (Achterberg et al., 2016; van den Bos et al., 2015). It is relevant to point out that the link between the concept of reward sensitivity (i.e., the extent to which a person likes and wants rewards in general; Harden et al., 2018) and amount sensitivity as we defined it in our study (i.e., a quantification of how much participants differentiate between the different amount levels when making their decisions) is somewhat unclear. Thus, whether stronger amount differentiation is part of heightened reward sensitivity during adolescence is unclear, and it may therefore not be subjected to nonlinear changes across adolescence.

Unlike amount sensitivity, delay sensitivity did not change with age. Based on previous suggestions that developmental increases in patience are due to increased future orientation (e.g., Steinberg et al., 2009; van den Bos et al., 2015) or increased cognitive control (e.g., Achterberg et al., 2016; Steinbeis et al., 2016), we expected that delays might have less impact with increasing age (i.e., because longer delays would seem closer or because sooner options would be more strongly suppressed, respectively). Instead, children, adolescents, and young adults all showed similar delay sensitivity, inconsistent with these accounts. Our results also seem inconsistent with de Water et al. (2017) and Mies et al. (2019), who found that specifically more patient adolescents showed less delay sensitivity. But although no ceiling effect was reached, the furthest time point in our study was only 42 days. Thus, future studies that use wider time ranges (and/or include younger children) might still find age-related decreases in delay sensitivity.

Another age-related change we found was that although adolescents and young adults weakly preferred immediate SS delivery over future SS delivery, children showed, if anything, the opposite pattern. Interestingly, this finding seems to imply that young adults and adolescents were tempted more by immediate rewards than children. However, this age-related change in present bias could also be due to a change in how *future* rewards were dealt with. It is possible that immediate SS options are tempting for all age groups, but that when both the SS and LL choices are future rewards, more delib-

erative thinking is triggered in adolescents and young adults (resulting in more LL choices)—whereas children opt for the nearest future (SS) reward instead, resulting in these opposite patterns. If so, age-related differences in the present bias may actually represent a developing future bias. Future research should replicate and verify this (also given previous mixed findings in adolescent-only studies; e.g., Laube et al., 2017, 2020).

More generally, this cross-sectional study was a first attempt to investigate amount and delay sensitivity across children, adolescents, and young adults, but we would recommend that future studies use a longitudinal within-participant approach. In addition, we would recommend collecting IQ and SES level information about the participants because these have been found to be associated with patience (Grandin et al., 2022; Wilson et al., 2011) and thus may have influenced our findings. Lastly, more concrete theoretical specification of the different developmental theories would be desirable because we often found it difficult to extrapolate what these theories might predict in terms of results. For example, how would amount sensitivity—an important part of intertemporal choice—be expected to change if cognitive control or future orientation were to increase with age? Interestingly, the few theoretical predictions we made (i.e., adolescent peaks and delay sensitivity changes) were not supported. Together, this argues for (a) better-specified theories that make clear predictions and (b) confirmatory hypothesis-driven studies to test those predictions.

To conclude, this study looked beyond age changes in overt intertemporal choice by investigating contributing underlying mechanisms across children, adolescents, and young adults. We found an adult-emergent increase in patience that could not be explained by insensitivity to delays or amounts in children because even children showed sensitivity to these relevant choice factors. Interestingly, delay sensitivity and amount sensitivity seem to develop across different timelines given that delay sensitivity did not change across children, adolescents, and adults, whereas amount sensitivity increased further with age. Thus, specifically increases in amount sensitivity seem to contribute to the age-related increase in patience level.

Data availability

Data, scripts, and stimuli are available at <https://osf.io/g2yf7>.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jecp.2023.105691>.

References

- Achterberg, M., Peper, J. S., van Duijvenvoorde, A. C., Mandl, R. C., & Crone, E. A. (2016). Frontostriatal white matter integrity predicts development of delay of gratification: A longitudinal study. *Journal of Neuroscience*, 36, 1954–1961. <https://doi.org/10.1523/JNEUROSCI.3459-15.2016>.
- Amlung, M., Marsden, E., Holshausen, K., Morris, V., Patel, H., Vedelago, L., Naish, K. R., Reed, D. D., & McCabe, R. E. (2019). Delay discounting as a transdiagnostic process in psychiatric disorders: A meta-analysis. *JAMA Psychiatry*, 76, 1176–1186. <https://doi.org/10.1001/jamapsychiatry.2019.2102>.

- Barr, D. J., Levy, R., Scheepers, C., & Tily, H. J. (2013). Random effects structure for confirmatory hypothesis testing: Keep it maximal. *Journal of Memory and Language*, 68, 255–278. <https://doi.org/10.1016/j.jml.2012.11.001>.
- Bürkner, P. (2017). brms: An R package for Bayesian multilevel models using Stan. *Journal of Statistical Software*, 80, 1–28. <https://doi.org/10.18637/jss.v080.i01>.
- Carpenter, B., Gelman, A., Hoffman, M., Lee, D., Goodrich, B., Betancourt, M., Brubaker, M., Guo, J., Li, P., & Riddell, A. (2016). Stan: A probabilistic programming language. *Journal of Statistical Software*, 76, 1–32. <https://doi.org/10.18637/jss.v076.i01>.
- Casey, B. J., Getz, S., & Galvan, A. (2008). The adolescent brain. *Developmental Review*, 28, 62–77. <https://doi.org/10.1016/j.dr.2007.08.003>.
- Demurie, E., Roeyers, H., Baeyens, D., & Sonuga-Barke, E. (2012). Temporal discounting of monetary rewards in children and adolescents with ADHD and autism spectrum disorders. *Developmental Science*, 15, 791–800. <https://doi.org/10.1111/j.1467-7687.2012.01178.x>.
- de Water, E., Cillessen, A. H. N., & Scheres, A. (2014). Distinct age-related differences in temporal discounting and risk taking in adolescents and young adults. *Child Development*, 85, 1881–1897. <https://doi.org/10.1111/cdev.12245>.
- de Water, E., Mies, G. W., Figner, B., Yoncheva, Y., van den Bos, W., Castellanos, F. X., Cillessen, A. H. N., & Scheres, A. (2017). Neural mechanisms of individual differences in temporal discounting of monetary and primary rewards in adolescents. *NeuroImage*, 153, 198–210. <https://doi.org/10.1016/j.neuroimage.2017.04.013>.
- Figner, B., Knoch, D., Johnson, E. J., Krosch, A. R., Lisanby, S. H., Fehr, E., & Weber, E. U. (2010). Lateral prefrontal cortex and self-control in intertemporal choice. *Nature Neuroscience*, 13, 538–539. <https://doi.org/10.1038/nn.2516>.
- Foerde, K., Figner, B., Doll, B. B., Woyke, I. C., Braun, E. K., Weber, E. U., & Shohamy, D. (2016). Dopamine modulation of intertemporal decision-making: Evidence from Parkinson disease. *Journal of Cognitive Neuroscience*, 28, 657–667. https://doi.org/10.1162/jocn_a_00929.
- Grandin, A., Guillou, L., Sater, R. A., Foucault, M., & Chevallier, C. (2022). Socioeconomic status, time preferences and pro-environmentalism. *Journal of Environmental Psychology*, 79. <https://doi.org/10.1016/j.jenvp.2021.101720>. Article 101720.
- Harden, K. P., Mann, F. D., Grotzinger, A. D., Patterson, M. W., Steinberg, L., Tackett, J. L., & Tucker-Drob, E. M. (2018). Developmental differences in reward sensitivity and sensation seeking in adolescence: Testing sex-specific associations with gonadal hormones and pubertal development. *Journal of Personality and Social Psychology*, 115, 161–178. <https://doi.org/10.1037/pspp0000172>.
- Kirby, K. N., & Herrnstein, R. J. (1995). Preference reversals due to myopic discounting of delayed reward. *Psychological Science*, 6, 83–89. <https://doi.org/10.1111/j.1467-9280.1995.tb00311.x>.
- Laube, C., Lorenz, R., & van den Bos, W. (2020). Pubertal testosterone correlates with adolescent impatience and dorsal striatal activity. *Developmental Cognitive Neuroscience*, 42. <https://doi.org/10.1016/j.dcn.2019.100749>. Article 100749.
- Laube, C., Suleiman, A. B., Johnson, M., Dahl, R. E., & van den Bos, W. (2017). Dissociable effects of age and testosterone on adolescent impatience. *Psychoneuroendocrinology*, 80, 162–169. <https://doi.org/10.1016/j.psyneuen.2017.03.012>.
- Lee, K., Bull, R., & Ho, R. M. (2013). Developmental changes in executive functioning. *Child Development*, 84, 1933–1953. <https://doi.org/10.1111/cdev.12096>.
- Lempert, K. M., Steinglass, J. E., Pinto, A., Kable, J. W., & Simpson, H. B. (2019). Can delay discounting deliver on the promise of RDoC? *Psychological Medicine*, 49, 190–199. <https://doi.org/10.1017/S0033291718001770>.
- Lenth, R. (2019). *emmeans: Estimated marginal means, aka least-squares means*. R package Version 1.3.4. <https://CRAN.R-project.org/package=emmeans>.
- Mazur, J. E. (1987). An adjusting procedure for studying delayed reinforcement. In M. L. Commons, J. E. Mazur, J. A. Nevin, & H. Rachlin (Eds.), *Quantitative analysis of behavior*, Vol. 5: *The effect of delay and intervening events on reinforcement value* (pp. 55–73). Lawrence Erlbaum.
- Mies, G. W., de Water, E., Wiersma, J. R., & Scheres, A. (2019). Delay discounting of monetary gains and losses in adolescents with ADHD: Contribution of delay aversion to choice. *Child Neuropsychology*, 25, 528–547. <https://doi.org/10.1080/09297049.2018.1508563>.
- Olson, E. A., Hooper, C. A., Collins, P., & Luciana, M. (2007). Adolescents' performance on delay and probability discounting tasks: Contributions of age, intelligence, executive functioning, and self-reported externalizing behavior. *Personality and Individual Differences*, 43, 1886–1897. <https://doi.org/10.1016/j.paid.2007.06.016>.
- Prelec, D., & Loewenstein, G. (1991). Decision making over time and under uncertainty: A common approach. *Management Science*, 37, 770–786. <https://doi.org/10.1287/mnsc.37.7.770>.
- Prencipe, A., Kesek, A., Cohen, J., Lamm, C., Lewis, M. D., & Zelazo, P. D. (2011). Development of hot and cool executive function during the transition to adolescence. *Journal of Experimental Child Psychology*, 108, 621–637. <https://doi.org/10.1016/j.jecp.2010.09.008>.
- R Core Team. (2018). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing. <https://www.R-project.org>.
- Rights, J. D., & Sterba, S. K. (2019). Quantifying explained variance in multilevel models: An integrative framework for defining R-squared measures. *Psychological Methods*, 24, 309–338. <https://doi.org/10.1037/met0000184>.
- Ripke, S., Hübner, T., Mennigen, E., Müller, K. U., Rodehacke, S., Schmidt, D., Jacob, M. J., & Smolka, M. N. (2012). Reward processing and intertemporal decision making in adults and adolescents: The role of impulsivity and decision consistency. *Brain Research*, 1478, 36–47. <https://doi.org/10.1016/j.brainres.2012.08.034>.
- Samuelson, P. A. (1937). A note on measurement of utility. *Review of Economic Studies*, 4, 155–161. <https://www.jstor.org/stable/2967612>.
- Steinbeis, N., Haushofer, J., Fehr, E., & Singer, T. (2016). Development of behavioral control and associated vmPFC-DLPFC connectivity explains children's increased resistance to temptation in intertemporal choice. *Cerebral Cortex*, 26, 32–42. <https://doi.org/10.1093/cercor/bhu167>.

- Steinberg, L. (2008). A social neuroscience perspective on adolescent risk-taking. *Developmental Review*, 28, 78–106. <https://doi.org/10.1016/j.dr.2007.08.002>.
- Steinberg, L., Graham, S., O'Brien, L., Woolard, J., Cauffman, E., & Banich, M. (2009). Age differences in future orientation and delay discounting. *Child Development*, 80, 28–44. <https://doi.org/10.1111/j.1467-8624.2008.01244.x>.
- Takahashi, T. (2009). Theoretical frameworks for neuroeconomics of intertemporal choice. *Journal of Neuroscience, Psychology, and Economics*, 2, 75–90. <https://doi.org/10.1037/a0015463>.
- Thaler, R. (1981). Some empirical evidence on dynamic inconsistency. *Economics Letters*, 8, 201–207. [https://doi.org/10.1016/0165-1765\(81\)90067-7](https://doi.org/10.1016/0165-1765(81)90067-7).
- van den Bos, W., Rodriguez, C. A., Schweitzer, J. B., & McClure, S. M. (2015). Adolescent impatience decreases with increased frontostriatal connectivity. *Proceedings of the National Academy of Sciences of the United States of America*, 112, E3765–E3774. <https://doi.org/10.1073/pnas.1423095112>.
- Westfall, J. E., Kim, C. M., & Ma, A. Y. (2012). Locking the virtual filing cabinet: A researcher's guide to internet data security. *International Journal of Information Management*, 32, 419–430. <https://doi.org/10.1016/j.ijinfomgt.2012.01.005>.
- Wilson, V. B., Mitchell, S. H., Musser, E. D., Schmitt, C. F., & Nigg, J. T. (2011). Delay discounting of reward in ADHD: Application in young children. *Journal of Child Psychology and Psychiatry*, 52, 256–264. <https://doi.org/10.1111/j.1469-7610.2010.02347.x>.