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SHORT REPORT

The reward positivity shows increased amplitude and decreased latency with increasing age in early childhood

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Abstract

The reward positivity (RewP) is a widely studied measure of neural response to rewards, yet little is known about normative developmental characteristics of the RewP during early childhood. The present study utilized a pooled community sample of 309 4- to 6-year-old children who participated in the Doors guessing game to examine the latency and amplitude of the RewP. Peak detection of the gain-loss difference waveform was conducted for electrodes Fz, Cz, Pz, Oz and the mean activity in a 100 ms window centered around this peak was analyzed. There was a significant decrease in RewP latency (RewP was earlier) and increase in RewP amplitude (RewP magnitude was larger) with advancing age in this cross-sectional analysis. Further, these were independent effects, as both RewP latency and RewP amplitude were uniquely associated with children's age. Moreover, our results indicate that the RewP latency in 4- to 6-year-olds falls outside the 250–350 ms window typically used to quantify the RewP (RewP latency in our sample = 381 ms; *SD* = 60.15). The internal consistency for latency (.64) and amplitude (.27) of the RewP were characterized by moderate to low reliability, consistent with previous work on the reliability of difference scores. Overall, results demonstrate RewP differences in both timing and amplitude across age in early childhood, and suggest that both amplitude and latency of the RewP might function as individual difference measures of reward processing. These findings are discussed in the context of methodological considerations and the development of reward processing across early childhood.

KEYWORDS
reward positivity, reward processing, RewP, ERP, development, childhood

1 | INTRODUCTION

Reward processing, including both the anticipation and outcome of reward, is salient in experiences of positive affect in daily life, with heterogeneous neural and physiological correlates. Individual differences in reward processing have been shown to play a key role in the onset and maintenance of several psychiatric disorders including depression (Luking et al., 2016; Nusslock & Alloy, 2017) and are associated with core symptoms of these disorders such as anhedonia (Stringaris et al., 2015). In children, there has been an increased focus on elucidating how early alterations in reward processing set the stage for poor outcomes including psychopathology, substance abuse, and poor decision making. To do so, it is important to generate further information on normative age-related variation in such processes.

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The reward positivity (RewP) is a widely used electroencephalogram (EEG) measure of neural response to rewards, yet little is known about the normative expression of the RewP during different developmental stages in young children. The RewP is an event related potential (ERP) that is time-locked to reward-based stimuli and indexes responses to positive outcomes relative to negative outcomes (Proudfit, 2015). Commonly measured at frontocentral sites, the RewP is thought to be maximal at FCz and is typically measured between 250 and 350 ms following stimulus onset (Krigolson, 2018). The RewP is also referred to by other names in the literature, including the medial frontal negativity (Gehring & Willoughby, 2002), feedback error-related negativity (Holroyd & Coles, 2002), and feedback negativity (Yeung et al., 2005); however, the term RewP appears to most precisely reflect the positivity that is present in response to rewards that is reduced or absent following non-rewards (e.g., Foti et al., 2011; Holroyd et al., 2008).

Although there has been increasing interest in examining developmental changes in the RewP across childhood and adolescence (Burani et al., 2019; Kujawa et al., 2018; Moser et al., 2018), there may be important differences in the manifestation of RewP as a function of age that have not been systematically investigated to date. The present study aims to further our understanding of the normative characteristics of early reward processing by investigating differences in the amplitude and latency of the RewP by age in a cross-sectional sample of 4- to 6-year-olds.

One of the most commonly used paradigms to elicit the RewP is the Doors Task, a simple guessing game in which participants choose one of two doors to reveal a symbol (feedback) that corresponds to either gaining or losing money or points. In this task, the RewP is operationalized as the difference between gaining and losing trials—a strategy that aims to remove the variance common to both responses. Importantly, there is evidence that the RewP in the Doors Task is a useful index of individual differences in reward sensitivity (Bress et al., 2012; Novak et al., 2016; Proudfit, 2015). Because of this, the RewP has been used to assess reward sensitivity in the context of depression – a disorder characterized by dysfunctions in reward sensitivity – often finding that RewP amplitude is blunted in depressed individuals (Bress et al., 2012, 2013; Foti & Hajcak, 2009; Foti et al., 2014; Liu et al., 2014). This body of work emphasizes the utility of the RewP as a measure of individual differences in reward sensitivity, but questions remain about the normative characteristics of the RewP in early childhood.

The simplicity of the Doors task allows it to be used across a wide range of ages and a small but growing literature extends this work downward to children as young as 3- to 4 years (Barch et al., 2018; Belden et al., 2016; Luby et al., 2019; Moser et al., 2018). In a sample of 124 children ranging from 3- to 14 years ($M_{age} = 8.02$; $SD = 2.38$), Moser et al. (2018) used the Doors task to examine age-related differences in the amplitude of the RewP. Across the sample, RewP amplitude increased with increasing age; RewP amplitude was also larger in boys than girls. Moreover, this increase in amplitude (but not the sex difference) was present when examining a subset of younger children (3- to 7 years), suggesting developmental changes in reward processing begin in early childhood and continue through adolescence. An increase in RewP amplitude was also found over a 2-year period in a sample of 8- to 14-year-old girls (Burani et al., 2019). However, other studies with children and adolescents have not found age-related changes in RewP amplitude (Bress et al., 2015; Kujawa et al., 2018; Lukie et al., 2014).

The majority of studies on early reward processing have focused on the *magnitude* of the RewP as a measurement of reward processing. However, the latency of the RewP also has the potential to provide important information about the time-course of reward processing, and may be particularly meaningful in the context of development (see Kappenman & Luck, 2012 for a review). Indeed, studies on other ERP components such as the P300 (commonly elicited in signal-detection tasks) find that latency decreases from early childhood through late adolescence (Dinteren et al., 2014), possibly reflecting developmental differences in the speed of cognitive processing or neural computations, and raise questions about whether RewP latency follows a similar pattern across development.

There is a dearth of research regarding RewP latency at any age. Whereas the vast majority of studies with older children and adolescents select the 250–550 ms or 275–357 ms window at frontocentral sites (e.g., Cz, FCz, Fz) for analyses (Bress et al., 2012, 2015; Burani et al., 2019; Kessel et al., 2016; Kujawa et al., 2014; Luking et al., 2017; Moser et al., 2018), the few RewP studies that exclusively test young children have selected wider windows (i.e., 250–550 ms) at more parietal recording sites (i.e., Pz; Barch et al., 2018; Belden et al., 2016; Luby et al., 2019). RewP windows are typically selected based on visual inspection of grand average waveforms and/or prior literature. Thus, the selection of different time-windows for older and younger children suggests a different RewP morphology in younger children – one that is possibly later. However, most children in these early childhood studies met criteria for preschool-onset depression, raising questions about whether scoring the RewP at a later time window and from a different site reflects differences in normative aspects of RewP latency and location in young children or is instead reflective of early psychopathology. Importantly, the field is lacking a systematic evaluation of the RewP in

RESEARCH HIGHLIGHTS

- Across a sample of 309 4- to 6-year-olds we demonstrate a systematic increase in RewP amplitude and decrease in RewP latency with increasing age
- RewP amplitude and RewP latency independently predicted age, suggesting each measure captures distinct age-related variance in reward processing in young children
- RewP latency is relatively unexplored but showed superior internal consistency to RewP amplitude, suggesting it may be a particularly robust index of reward processing in childhood
- RewP latency fell outside the typical window used to quantify the RewP in adolescents/adults, supporting the use of difference-wave peak measures to capture target components

TABLE 1 Sample demographics by age group

	4-year-olds ($n = 94$)	5-year-olds ($n = 127$)	6-year-olds ($n = 88$)	Statistic	p
Demographics					
Age: Mean (SD)	4.50 (.27)	5.44 (.30)	6.53 (.29)		
Sex (%girls)	42 (45%)	59 (47%)	47 (53%)	$x(_{2})^{2} = 1.57$	.457
Race					
White	67 (71%)	83 (65%)	57 (65%)	$x(_{4})^{2} = 2.12$	.713
Black	10 (11%)	19 (15%)	10 (11%)		
Bi/multi-racial; other	17 (18%)	25 (20%)	21 (24%)		
Income-to-needs					
($n = 299$)	3.28 (1.96)	3.44 (1.95)	3.05 (1.82)	$F(_{2}) = 1.04$	.354

early childhood that would inform our understanding of the normative expression of this commonly used neural measure of reward processing.

1.1 | Present study

The present study aims to further our understanding of the normative developmental characteristics of reward processing by investigating differences in the RewP as a function of age across early childhood in a community sample of 4- to 6-year-old children. The study examines age-related developmental differences in both RewP amplitude and RewP latency to provide a more comprehensive account of early reward processing. To assess latency, peak detection methods were employed to capture the 100 ms window surrounding the peak of the RewP in difference waveform at multiple sites along midline (Fz, Cz, Pz, Oz). Unlike previous studies that restricted peak detection to the 250–350 ms window following stimulus onset (Burani et al., 2019; Lukie et al., 2014) the present study used an expanded window of 250–550 ms to avoid artificially truncating the potential range of RewP peaks. This data-driven approach thus has the potential to detect individual differences in RewP latency while also providing a more precise estimate of RewP amplitude that can be examined as a function of age to investigate developmental changes in reward processing in early childhood.

2 | METHOD

2.1 | Participants

Participants were 309 4- to 6-year-old children ($M = 5.46$, $SD = .83$) pooled across four studies conducted between 2015–2020 in the Early Emotional Development Program (EEDP) at Washington University School of Medicine (WUSM). Table 1 presents demographic details including sex, race, and income-to-needs (a measure of family income that accounts for number of people in the household). An additional 17 children were excluded from analyses because they had < 33% usable ERP segments in either the gain or loss condition ($n = 9$) or for poor quality ERP data based on visual inspection of the waveform at electrode Cz ($n = 8$). Of the children included in the final sample, there were no significant differences in number of usable ERP segments (out of 60) as a function of age: 4-year-olds ($M = 57.70$, $SD = 4.16$, R = 40-60), 5-year-olds ($M = 57.85$, $SD = 4.43$, R = 38-60), 6-year-olds ($M = 58.81$, $SD = 3.33$, R = 40-60), x^{2} (36, $N = 309$) = 43.30, $p = .188$ (see Supplement Table 1 for additional details).

Sample selection

All studies conducted in the EEDP between 2015 and 2020 that included 4- to 6-year-olds, administered the Doors Task, and did not explicitly recruit children based on psychopathology were included. Within the four studies meeting these criteria, all children who were ages 4–6 years of age at their EEG session were included. Children were recruited from the community via flyers, online, radio, and physical ads, and from local schools to take part in a research study that included a lab visit to collect child EEG/ERP and behavioral measures along with parent-reports. All studies excluded children with neurologic problems or significant developmental delays or disorders (e.g., Autism Spectrum Disorder). Studies were approved by the WUSM Institutional Review Board. Written consent from caregivers and verbal assent from children was obtained for all participants.

2.2 | Design and procedure

2.2.1 | Doors task (ERP)

Children completed the Doors Task (Proudfit, 2015). A total of 30 gain trials and 30 loss trials were administered across three blocks of 20 trials each. Children were taught that on each trial they could either win 10 points or lose 5 points; points were later traded for a prize. Each trial starts with a fixation cross that appears for 1000 ms, followed by an image of two identical doors. The two doors stay up until the child presses a button to select a door (using the left or right game controller button), followed by another fixation cross for 1000 ms. Then the child receives feedback about whether they won 10 points (green up arrow) or lost 5 points (red down arrow), shown for 2000 ms. Lastly, another fixation cross is presented for 1500 ms. The task structure, including points accumulated and final outcome (winning 150 points, enough for a prize) was consistent across participants.

2.2.2 | EEG recording & data reduction

For all four studies, continuous EEG was recorded using the BrainVision ActiChamp 32 channel active channel amplifier system (BrainVision LLC). Setup included four additional AUX channels for the facial electrodes recording the electrooculogram (EOG) produced by eye movements and blinks. The vertical EOG was recorded from electrodes placed above and below the right eye, and the horizontal EOG was recorded from electrodes placed to the right of the right eye and the left of the left eye. An additional ground for the EOG signals was placed above the left eye. This EEG/ERP system is used with a 32-channel actiCAP active electrode cap in the 10/20 system, with caps for different sized child heads. Recordings were taken from 32 scalp electrodes and two electrodes on the mastoids. The EEG was sampled at 500 Hz and referenced online to electrode Cz. Off-line analysis was performed using Brain Vision Analyzer software (Brain Products, Germany) with data re-referenced to the average of Tp9 and Tp10, band-pass filtered from 0.1 to 30 Hz, and epoched from 200 ms before to 1000 ms after stimuli onset. The EEG was corrected for EOG artifacts using the procedure from Gratton and colleagues (Gratton et al., 1983). Specific intervals for individual channels were rejected in each trial using an automated procedure, with physiological artifacts identified by the following criteria: a voltage step of more than 50 μV between sample points, a voltage difference of 175 μV within a trial, and a maximum voltage difference of less than 0.5 μV within 100-millisecond intervals. The activity in the 200 ms window before feedback onset served as the baseline.

2.2.3 | Peak detection and data analysis

Peak detection (i.e., identifying the most positive peak of the gain-loss difference waveform) was conducted independently for electrodes Fz, Cz, Pz, and Oz within the 250–500 ms window following feedback in the gain minus loss ERP difference. Following this automated process the peaks were visually inspected and confirmed (or changed when appropriate) by three researchers (C.G., D.K., E.F.) who were aware of the general sample characteristics but blind to pertinent demographic details for individual participants, including specific age. Next, the 100 ms area centered around the peak (RewP) was selected for analysis. Amplitude was maximal at Cz, thus Cz was primarily used in subsequent analyses. There were no outliers greater than two standard deviations at electrode Cz.

Zero order correlations were first conducted to examine the relationships between age, latency, and amplitude. In order to examine age differences, separate linear regressions tested for differences in RewP amplitude and latency as a function of age (with age as a continuous variable, operationalized as age in months in all analyses). Then, in order to test whether latency and amplitude independently predicted age, amplitude and latency were included in the same regression model. All reported analyses covary for sex. Secondary exploratory analyses included income-to-needs and study, neither of which significantly predicted RewP amplitude or latency or substantively affected any findings (see Supplement Table 2). Income-to-needs was included as an exploratory variable based on broad findings that link childhood adversity with reward processing (see McLaughlin & Sheridan, 2016).

To examine psychometric properties of the RewP in this age range, the internal consistency of the RewP was assessed by calculating separate averages for even and odd trials for amplitude and latency (Levinson et al., 2017) and adjusted using the Spearman-Brown formula (Nunnally et al., 1967). Moderation analyses to assess whether internal consistency varied as a function of age were conducted using the PROCESS v3.5 macro for SPSS, (2017). Age was entered as continuous moderator of the relationship between even and odd trials, and the age interaction examined for significance.

Although all analyses were conducted using age in months as a continuous variable, means and standard deviations are presented for each electrode (Table 2), and the 10th, 25th, 50th, 75th, and 90th percentiles for electrode Cz (Table 3) for RewP amplitude and latency by age group (4 year, 5 year, 6 year) and the total sample, to illustrate age-related differences and facilitate comparisons to the extant literature. The choice of percentile cut-points and approach to determining normality is modeled on recent work establishing norms for the ERN in young adults (Imburgio et al., 2020). Prior to calculating the percentiles, the distributions were examined for normality. Visual inspection of density and Q-Q plots for RewP amplitude and latency and their corresponding residuals determined that these distributions across the sample appeared normal.

3 | RESULTS

Internal consistency for RewP amplitude and latency were .27 ($p = .007$) and .64 ($p < .001$), respectively. Age did not moderate internal consistency for either amplitude $F(1, 305) = .129$, $p = .719$ or latency $F(1, 305) = .214$, $p = .644$. The relatively modest reliability for RewP amplitude is consistent with prior literature in older children and adolescents and is unsurprising given that difference scores tend to yield lower reliability (Bress et al., 2015; Levinson et al., 2017; Luking et al., 2017).[1]

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[1] Given prior literature demonstrating that internal consistency scores for gains and losses independently typically range from good to excellent (e.g., Bress et al., 2015), and the gap regarding the internal consistency of gains and losses at this young age, we used the average latency for each age group to select the 100ms window surrounding the peak and examined the internal consistency between gains and losses separately in this window. The internal consistency was good for gains (r=.83, p<.001) and acceptable for losses (r=.76, p<.001). Age did not moderate internal consistency for gains. There was some indication that age might moderate internal consistency for losses $F(1, 305)=2.10$, p=.036, however this exploratory finding did not survive corrections for multiple comparisons.

TABLE 2 Means and standard deviations by age group for the amplitude and latency of the waveforms at electrodes Fz, Cz, Pz, and Oz

	Fz	Cz	Pz	Oz
Amplitude				
4	3.78 (7.68)	4.01 (8.79)	1.80 (7.80)	2.75 (8.12)
5	2.26 (7.43)	5.60 (6.77)	4.43 (7.23)	3.54 (6.58)
6	4.53 (8.18)	7.76 (8.15)	5.70 (7.85)	4.78 (7.73)
M (SD)	3.37 (7.95)	5.73 (7.93)	3.99 (7.72)	3.68 (7.43)
Latency				
4	393.51 (62.18)	391.64 (60.91)	391.98 (59.54)	391.33 (59.32)
5	382.88 (61.22)	383.40 (62.04)	384.24 (60.00)	381.48 (56.43)
6	371.02 (54.31)	369.52 (54.85)	368.91 (52.12)	371.11 (51.89)
M (SD)	382.74 (60.07)	381.03 (60.15)	382.23 (58.24)	381.50 (56.43)

TABLE 3 Amplitude and latency corresponding to percentile cut-points and means (standard deviations) for the RewP at Cz. able 3

%ile	4-year-olds	5-year-olds	6-year-olds	Total sample
RewP amplitude (Cz)				
90th	14.83	14.30	18.18	16.07
75th	9.90	9.45	12.95	10.33
50th	4.08	5.86	6.43	5.79
25th	−2.47	.80	1.46	.50
10th	−6.75	−3.26	−1.83	−4.05
M (SD)	4.01 (8.79)	5.60 (6.77)	7.76 (8.15)	5.73 (7.93)
RewP latency (Cz)				
90th	463.00	474.40	448.40	464.00
75th	436.00	426.00	400.00	424.00
50th	400.00	384.00	367.00	384.00
25th	345.50	340.00	336.50	340.00
10th	299.00	301.20	297.60	300.00
M (SD)	391.64 (60.91)	383.40 (62.04)	369.52 (54.85)	381.95 (60.15)

Zero order correlations revealed significant associations between age and RewP amplitude ($r = .16$, $p = .006$), and age and RewP latency ($r = -.17$, $p = .002$), but not between RewP amplitude and RewP latency ($r = .03$, $p = .611$). Consistent with these correlations and the impression from Figures 1–3, the linear regressions controlling for sex demonstrated that RewP amplitude increased with age, $B = 1.50$, $t = 2.78$, $p = .006$, 95%CI(.44–2.56). In addition, RewP latency decreased as a function of age, $B = -12.59$, $t = -3.09$, $p = .002$, 95%CI(−20.61–−4.57). Neither RewP amplitude, $B = .36$, $t = .41$, $p = .685$, 95%CI(−1.40-2.14), nor RewP latency, $B = 5.24$, $t = .77$, $p = .439$, 95%CI(−8.08-18.55), differed as a function of sex. When included in the same model, both RewP amplitude, $B = .02$, $t = 2.78$, $p = .006$, 95%CI(.005-.028) and RewP latency, $B = .002$, $t = -3.01$, $p = .002$, 95%CI(-.004–-.001) were independently related to age. Overall, these findings indicate that from 4- to 6-years of age children's response to reward both begins earlier and shows a progressive increase in magnitude with increasing age.

4 | DISCUSSION

The present work details age-related differences in both amplitude and latency of the RewP in a sample ranging in age from 4- to 6 years. Specifically, across this developmental period there was a systematic increase in RewP amplitude and a decrease in RewP latency with increasing age. Indeed, both amplitude and latency independently predicted age, indicating they are distinct measures that capture different aspects of age-related variance in the RewP. Whereas RewP amplitude is often studied as an individual difference measure, RewP latency is a relatively unexplored aspect of reward processing that indexes the speed of, and associated neural computations underlying, reward response. In the present study RewP latency showed superior internal consistency compared to the modest internal consistency of RewP amplitude, suggesting that RewP latency may be a particularly robust index of reward processing in childhood. This finding raises important questions about what other individual difference measures RewP latency may relate to beyond age. Finally, age did not moderate the internal consistency of either RewP amplitude or latency, supporting the notion that the RewP can be reliably measured in children as young as 4 years.

The increase in RewP amplitude from 4- to 6-years in the present study is consistent with Moser et al. (2018), which showed an increase in RewP amplitude across 3- to 14 years. The present study bolsters these findings with a substantially larger sample size and narrower age range allowing for increased confidence in the validity of an increase in RewP amplitude across early childhood. There are at least three possible explanations for this increase. One is that older children value the rewards more strongly than younger children, and the increased RewP amplitude reflects a stronger reward response. Alternatively,

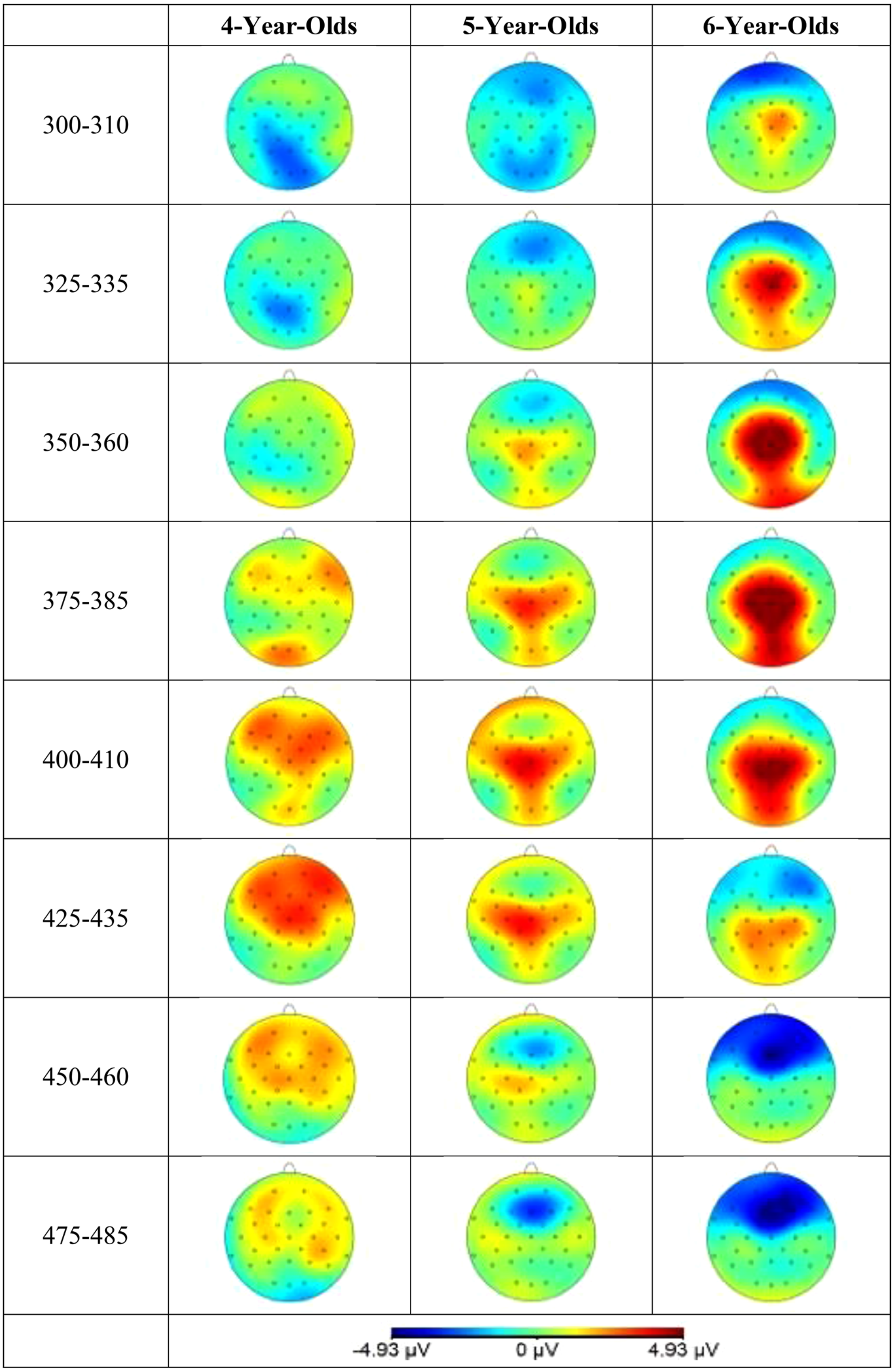

FIGURE 2 Voltage distribution in 10 ms increments across the 300–485 ms window following feedback

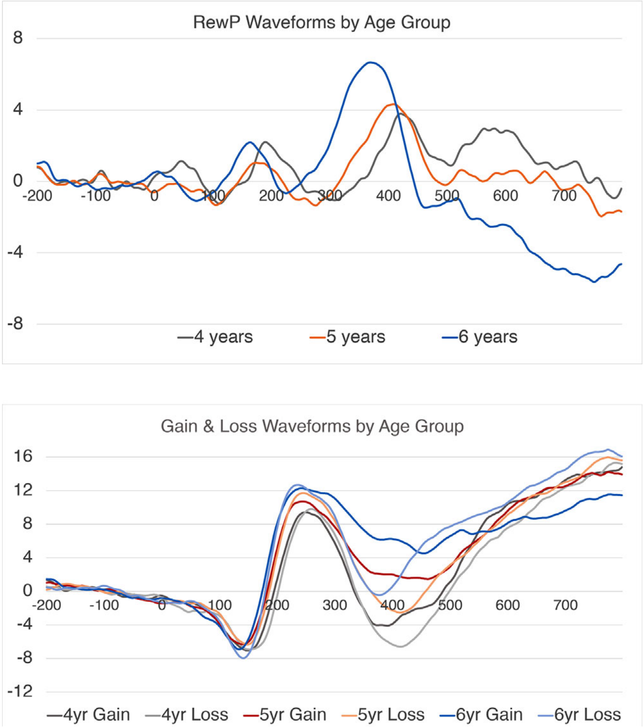

FIGURE 1 ERP waveforms by age group at Cz for the RewP (above) and separately for gains and losses (below)

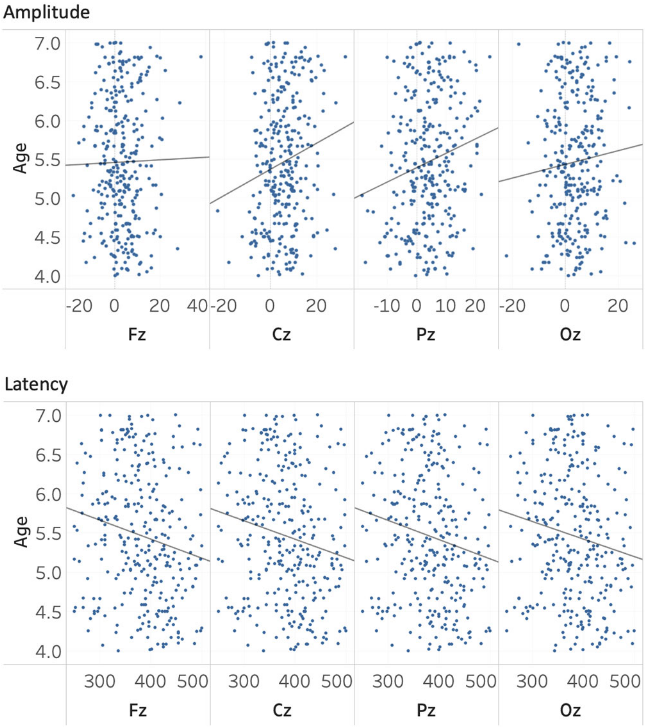

FIGURE 3 Scatterplots and regression lines for amplitude (above) and latency (below) plotted as a function of age (as a continuous variable) for each of four electrodes: Fz, Cz, Pz, and Oz

the increase may reflect improvements in action-outcome contingency awareness and learning (i.e., linking door choice to the outcome), or differences in task comprehension or competence that increase with age. For example, younger children may have decreased task competence (e.g., difficulty remembering instructions, trouble linking door choice to button press, remaining still) relative to older children. This explanation aligns with findings demonstrating that cognitive load decreases the RewP amplitude in adults (Krigolson et al., 2012, 2015). Moreover, these explanations are not mutually exclusive and multiple factors likely contribute to RewP amplitude increasing across early childhood.

The most striking and novel finding of the present work is the clear decrease in RewP latency across 4- to 6-years. The decreased latency of the RewP might reflect changes in the quality, time, intensity, or energy expenditure of the neural computations performed when processing reward (Poldrack, 2015). For example, younger children might face increased task demands (e.g., remaining still, remembering instructions) that require more cognitive control, which could prolong the processing of the primary task response; older children might recognize and differentiate valenced feedback more quickly (and potentially more accurately) due to reduced redundancy in coding of relevant information or improved structural network organization (see Poldrack, 2015, for further discussion of these possibilities). These possibilities, however, are speculative, and further studies are needed to address the mechanisms that underlie these age-related differences in RewP latency.

It will be important for future studies to investigate the mechanisms underpinning the larger RewP amplitude and earlier RewP latency that are seen as a function of increasing age. For example, examining concurrent measures of cognition and executive functioning might allow us to discern whether (or, potentially, which of) these age-related changes are specific to reward processing versus reflecting more global changes in neural processing. Future studies should also continue to assess RewP latency in older children and adolescents to determine the trajectory of the decrease in RewP latency across childhood, and also evaluate potential developmental changes in the latency of other ERP components such as the N2 and P300 in the context of paradigms designed to elicit them.[2]

Importantly, the average RewP latency for both the entire sample *and* for each age group falls outside the 250–350 ms window typically used to select the RewP. Thus, whereas prior studies that used the 250–350 ms window with young children likely captured some aspect of the RewP, those studies likely missed important information in the waveform at later timepoints and, notably, would have missed more information relevant to younger relative to older children. This finding has methodological implications as it indicates selecting a window

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[2] To investigate whether age-related latency changes in the RewP were due to earlier ERP latency differences, the latency of the N2 was examined using similar procedures to those used to detect the RewP. Peak detection was conducted on the gain-loss difference waveform at Oz (where the N2 was maximal) within the 200-300ms window following gain/loss feedback. Age did not significantly predict N2 latency, *B*=.05, *t*=.94, *p* = .346, 95%CI(-.46-1.31). Furthermore, the relationship between age and RewP latency remained significant when controlling for N2 latency, *B*=-.17, *t*=-2.92, *p*=.004, 95%CI(-.19.95—3.87), suggesting the age-related changes in RewP amplitude are independent of prior processes. Interestingly, exploratory analyses revealed a significant age-related increase in N2 amplitude, *B*=-.33, *t*=-6.16, *p*<.001, 95%CI(-12.67—6.53), indicating that age-related changes in amplitude are not limited to the RewP.

by visual inspection of the grand average waveform results in a protracted (smeared) RewP and obscures critical information about sample sub-groups. This finding also raises questions about whether information about meaningful individual differences are also obscured (e.g., differences as a function of psychopathology). It thus appears prudent to consider the peak of the difference waveform when beginning work with unique (e.g., young) samples – even when using established ERP components – to empirically test assumptions regarding latency of the target component.

The present study did not detect sex differences in RewP amplitude. In contrast, studies with older children and adolescents often find larger RewP amplitudes in boys relative to girls (Burani et al., 2019; Kujawa et al., 2019; Moser et al., 2018). However, this finding is consistent with the lack of sex differences in Moser et al.'s subsample of 3- to 7-year-olds and raises questions for future studies regarding the onset and development of these differences and associated mechanisms.

One limitation of the present study is that because the RewP is a difference score, it has inherently lower reliability—yet there was sufficient reliable variance to relate RewP to other individual difference measures (Patrick et al., 2019). Moreover, the reliability of the RewP amplitude in this age group, which has not been previously reported, was comparable to that of adults (Levinson et al., 2017), and the RewP latency had even better reliability. However, as a high percentage of usable data was obtained across the 60 trials, future studies could test whether increasing the number of trials improves internal consistency.

A second limitation concerns the utility of the reported percentile scores. Methodological decisions, including choice of recording system, ocular correction procedures, and baseline window, may all affect the ERP distribution (Klawohn et al., 2020). The relatively small sample size in each age group further suggests the need for caution when considering these percentiles. However, as normative data for these age groups is lacking in the extant literature, percentile scores from the current data are presented to demonstrate relative differences in percentiles as a function of age group and provide a foundation for future research.

A third limitation concerns the lack of overlap between behavioral measures across the studies concerning known correlates of reward processing (e.g., depressive symptoms, stress reactivity). This information will be important to obtain in future studies to examine how individual differences affect the development of reward processing. However, the aim of the present study was to characterize normative development of reward systems which is needed in order to contextualize the effects of individual differences in the future. Finally, whereas the present cross-sectional results provide compelling evidence for age-based differences in the RewP, longitudinal data is needed to make definitive claims that the differences detected in the present study truly reflect developmental changes.

In sum, the present study demonstrates systematic increases in RewP amplitude and decreases in RewP latency in early childhood. These components uniquely predict age, suggesting each measure captures distinct age-relate variance in reward processing in young children. The findings also provide strong support for the use of methodological approaches that capitalize on difference-wave peak measures to select ERP segments for analysis in order to more precisely quantify RewP amplitude while also measuring RewP latency, and highlight the danger of truncating the desired component in one or more subgroups when the onset of that component occurs significantly earlier or later than is identified by the grand average or the commonly accepted window. Investigating what other individual difference measures RewP latency relates to beyond age will be an important next step toward informing our understanding of the normative development of reward processing and furthering its use as a marker of psychopathology.

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CONFLICT OF INTEREST

None of the authors report any conflicts of interest. All study procedures were approved by the Washington University Institutional Review Board and participants in the research were treated in accordance with the ethical standards of the APA.

DATA AVAILABILITY STATEMENT

The data that support the findings of the study are available from the corresponding author upon reasonable request.

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