Reward boosts number acuity in adolescents with developmental dyscalculia

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Abstract

Developmental dyscalculia (DD) is a neurodevelopmental disorder characterized by persistent difficulties in numerical processing, often linked to atypical functioning of fronto-parietal brain networks. Despite its considerable social, economic, and psychological impact on individuals and society, existing interventions targeting numeracy in DD have shown limited efficacy. This highlights the urgent need for more effective strategies to support numerical learning in individuals with DD. In the present study, we propose an ecologically valid and easy-to-implement approach based on reward to enhance numerical abilities in adolescents with DD matched to controls. Our findings demonstrate, for the first time, that even modest monetary incentives can improve basic numerical processing in this population, suggesting a cost-effective and scalable means of supporting cognitive intervention. The observed effects of rewards may reflect increased stimulus salience through dopaminergic–noradrenergic interactions, potentially engaging attentional-parietal networks involved in quantity representation. This study highlights the feasibility of leveraging reward-based strategies in everyday settings—such as homes or schools—to support adolescents with numerical difficulties.

Keywords: Motivation; Incentive; Attention; Intervention; Neurodevelopmental Disorders

Introduction

Numeracy difficulties impose an estimated £2.4 billion annual cost only in the UK [1,2] and are associated with significant daily-life challenges, including difficulties in financial management and medication dosing. Persistent numeracy difficulties can stem from atypical brain development– best known as developmental dyscalculia (DD) [3]. Notably, low numeracy during development may lead to severe psychopathological consequences, such as anxiety and depression, as well as reduced economic prosperity in adulthood [4]. For this reason, interventions to improve numerical difficulties have flourished in the last decades. Training programs are generally designed to develop number abilities [5–8] and enhance problem-solving strategies [9] through mentoring and tutoring [10]. Nevertheless, their efficacy is often limited [11,12], urging the development of novel approaches that can enhance interventions' outcomes.

Recently, one such interventions consisted of facilitating neuroplastic changes by applying brain stimulation over specific cerebral regions (e.g., parietal or frontal) which are known to be engaged during numerical processing [13–15]. This approach – which is promising but still developing due to the very limited number of studies including DD [16,17] – is intrinsically limited in its applicability to real-world settings – particularly within school-based or home-based programs [18–20].

A more ecological and ease-to-implement strategy to boost numerical abilities involves the use of reward [21–24]. The effect of reward on performance improvement during development has been demonstrated in several fields, such as attention [25], memory [26], inhibitory control [27–29], decision making [30], conflict resolution [31], and cognitive control [32]. Recently, reward has been shown to modulate numerical processing in typical development (TD) children and adolescents [33]. While the study of reward modulation has been extended to atypical development and is actively promoted to enhance educational and behavioral programs in several developmental disorders (e.g., autism [34]; ADHD [35]), its application to DD remains unexplored.

Reward influences behavior by modulating dopaminergic circuits [21–24]. Dopamine, a key neurotransmitter, plays a central role in shaping cellular physiology by modulating synaptic plasticity [36], altering neuronal excitability [37,38], and enhancing the signal-to-noise ratio [39]. At the neural level, the reward network comprises striatal structures innervated by mesolimbic and nigrostriatal dopaminergic projections [40]. These structures are functionally connected to frontal regions—particularly the anterior cingulate cortex (ACC) and the dorsolateral prefrontal cortex (dlPFC) —as well as to parietal regions [22,41,42].

Here, we present findings on the modulation of reward processing in DD, characterized by consistent fronto-parietal dysfunction [14,43,44]. This neural network which plays a crucial role in numerical processing [14,43,44] is also functionally involved during reward processing [22,41,42].

Using an established experimental paradigm [45–47], 61 adolescents, including 31 with DD (the DD Group) and 30 with typically developing controls (the TD Group), completed a remotely administrated, home-based *numerosity discrimination task* adapted to include monetary reward (see Figure 1 and Methods section). The numerosity discrimination task is a widely used task to measure number acuity, or the Approximate Number System (ANS) precision, whereby participants typically identify which of two arrays of dots contains more elements [45–47]. The ANS is an intuitive and innate ability which enables rapid, although approximate estimations of the number of sensory stimuli presented (e.g. visual or auditory [44]). The successful development of the ANS – usually indexed as *weber fraction (wf)* – predicts later school-based arithmetic achievement [45,48–54], and poor number acuity is strongly associated with DD [44].

Two potential outcomes may emerge from the present study:

i) The DD group my perform similarly to the TD group in reward vs no-reward conditions, indicating preserved reward mechanisms in DD. In this case, it may be reasonable that dopamine, released by reward stimuli, could act as an indirect endogenous modulator of fronto-parietal numerical representations (Nieder, 2024).

ii) Alternatively, the DD group may not benefit from reward, suggesting dysfunction within the reward system. This would create opportunities for further research into the disrupted neural mechanisms underlying reward processing in DD. Previous lesion studies already demonstrated that cognitive performance can be improved through reward-based modulation in individuals with localized fronto-parietal brain damage [55]. These results referred to a specific location of brain damage, providing new insights into the roles of subcortical and cortical areas in the relationship between attention and reward. Similarly, from a developmental perspective, our findings could offer new insights into the mechanisms through which reward interacts with atypical numerical processing in developing brains when compared to TD peers.

In this context, we strategically involved adolescents, as reward-based approaches have been shown to be particularly effective in this population [33]. This is likely due to adolescents' increased reward sensitivity, which stems from the imbalance between the delayed maturation of the dlPFC —crucial for top-down regulation of dopamine release— and the earlier development of dopaminergic projections from subcortical regions to the frontal cortex [22]. Current intervention programs for DD are typically targeted at early learners or children in primary school, while adolescents often remain a neglected age group [56].

Here Figure 1

Results

Accuracy and reaction times. Performance was first analyzed in terms of accuracy and reaction times (RTs) in two independent linear mixed-effects models. The model for accuracy revealed a main effect of Reward ($F(1,385) = 9.91$, $p < 0.01$, $\eta p^2 = 0.03$), Group ($F(1,54) = 6.01$, $p < 0.05$, $\eta p^2 = 0.1$), and Ratio ($F(3,385) = 551.26$, $p < 0.001$, $\eta p^2 = 0.81$). Accuracy was significantly higher in reward (mean=0.83, SD=0.12) compared to no-reward trials (mean=0.82, SD=0.13, see Fig. 2), which may indicate a beneficial reward effect. Accuracy was significantly lower in the DD Group (mean=0.81, SD=0.13) compared to the TD Group (mean=0.84, SD=0.12, see Fig. 2). Like in previous studies on similar paradigms [33,57], accuracy also decreased with difficulty and was at ceiling in the easiest ratios (Ratio 0.5: mean=0.97, SD=0.05; Ratio 0.75: mean=0.86, SD=0.09; Ratio 0.83: mean=0.76, SD=0.08; Ratio 0.88: mean=0.71, SD=0.08, see Tables S8 and S9 in Supplementary Results). No interactions reached significance (all $p > 0.05$).

Here Figure 2

The model for RTs revealed a main effect of Ratio ($F(3,385) = 173.65$, $p < 0.001$, $\eta p^2 = 0.58$), and a significant two-way interaction of Ratio by Reward ($F(3,385) = 3.31$, $p < 0.05$, $\eta p^2 = 0.03$). Reward increased RTs in the most difficult ratios (Ratio 0.88: $t(56)=3.28$, $p < 0.001$; Ratio 0.83: $t(56)=2.15$, $p < 0.05$, see Fig. 3) but not in the easier ones (Ratio 0.75: $t(56)=0.05$, $p > 0.05$; Ratio 0.5: $t(56)=1.74$, $p > 0.05$, see Fig. 3). This indicates a slowing of response speed under reward anticipation as task difficulty increased. There was also a Ratio by Group interaction ($F(3,385) = 5.65$, $p < 0.001$, $\eta p^2 = 0.04$), due to a tendency of the TD Group to increase RTs as task difficulty increased (see Fig. 3). No further main effects nor interactions were significant (all p > 0.05; see Tables S6 and S7 in Supplementary Results).

Here Figure 3

Number acuity. While the results so far suggest that reward enhances behavioral performance in both the DD and TD groups, *wf* is a more refined index of number acuity[5]. Therefore, a linear mixed-effects model for *wf* was run, revealing main effects of Reward ($F(1,52) = 7.32$, $p < 0.01$, $\eta p^2 = 0.12$) and Group ($F(1,51) = 8.17$, $p < 0.01$, $\eta p^2 = 0.14$). The *wf* was larger (i.e. performance was worse) in no-reward (mean=0.26, SD=0.09) compared to reward trials (mean=0.24, SD=0.08, see Fig. 4). This indicates that reward improved number acuity in both the TD and the DD groups. As expected, the *wf* was larger (i.e. performance was worse) in the DD Group (mean=0.28, SD=0.09) compared to the TD Group (mean=0.23, SD=0.08, see Fig. 4).
No further main effects nor interactions were significant (see Table S5 in Supplementary Results).

Here Figure 4

EZ-diffusion model. To characterize the reward-sensitive processes underlying the dual-choice numerosity discrimination task, we adopted the EZ-diffusion model (Wagenmakers et al., 2007). The EZ-diffusion model allows for the decomposition of trial-by-trial choices into their underlying dynamic decision-making components, including drift rate (ν), boundary separation (*a*), and non-decision time (t_{ER}).
With regard to *drift rate* (ν) component, which indicates the speed of evidence accumulation process, the linear mixed-effects model revealed a main effect of Reward ($F(1,371) = 5.02$, $p < 0.05$, $\eta p^2 = 0.01$), of Group ($F(1,52) = 11.48$, $p < 0.01$, $\eta p^2 = 0.18$), of Ratio ($F(3,371) = 354.59$, $p < 0.001$, $\eta p^2 = 0.74$) and a significant two-way interaction of Ratio by Group ($F(3,371) = 10.34$, $p < 0.001$, $\eta p^2 = 0.08$). The drift rate was higher in reward trials (mean=0.20, SD=0.15) compared no-reward trials (mean=0.18, SD=0.14, Fig. 5). While the drift rate was lower in the DD Group (mean=0.17, SD=0.12) compared to the TD Group (mean=0.21, SD=0.16). These findings suggest that reward enhances processing efficiency in both the DD and TD groups, although adolescents with DD exhibit an overall slower rate of evidence accumulation. The significant two-way interaction was driven by a greater

increase in drift rate in the easiest ratio (i.e., 0.5) for the TD group (see Fig. 5). No further interactions were significant ($p > 0.05$; see Tables S10 and S11 in Supplementary Results).

Here Figure 5

Considering *boundary separation* (*a*), which refers to a decision threshold parameter, the linear mixed-effects model revealed a main effect of Ratio ($F(1,350) = 84.28$, $p < 0.001$, $\eta p^2 = 0.42$) and a significant two-way interaction of Ratio by Group ($F(3,350) = 7.82$, $p < 0.001$, $\eta p^2 = 0.06$). Boundary separation decreased with increasing difficulty (Ratio 0.5: mean = 0.22, SD = 0.14; Ratio 0.75: mean = 0.11, SD = 0.02; Ratio 0.83: mean = 0.10, SD = 0.02; Ratio 0.88: mean = 0.10, SD = 0.02). This finding documented less conservative response criterion in both groups as task difficulty increased. A significant three-way interaction among Ratio, Group, and Reward ($F(3,350) = 4.04$, p < 0.01, $\eta p^2 = 0.03$) also emerged. This interaction was driven by the significant difference between the two groups (DD vs. TD adolescents) in the combination of Ratio 0.5 and reward condition; no other significant differences emerged between the two groups in the other conditions. However, the distribution of boundary separation was unusual for Ratio 0.5, and the model's results may not be reliable due to a violation of assumptions (specifically, a strong violation of homoscedasticity). No further main effects nor interactions were significant ($p > 0.05$; see Tables S12 and S13 in Supplementary Results).

Last, a linear mixed-effects model for non-decision time (t_{ER}) (e.g., sensory encoding or response execution) revealed a main effect of Ratio ($F(1,371) = 89.37$, $p < 0.001$, $\eta p^2 = 0.42$). Non-decision time increased with difficulty (Ratio 0.5: mean=0.34, SD=0.13; Ratio 0.75: mean=0.46, SD=0.11; Ratio 0.83: mean=0.50, SD=0.11; Ratio 0.88: mean = 0.51, SD = 0.11). There was also a Ratio by Group interaction ($F(3,371) = 5.01$, $p < 0.01$, $\eta p^2 = 0.04$), due to a tendency of the TD Group to increase non-decision time as task difficulty increased. No further main effects nor interactions were significant ($p > 0.05$; see Tables S14 and S15 in Supplementary Results).

Discussion

In the current study, adolescents with and without DD completed a home-based, remotely administered numerosity discrimination task with performance-contingent monetary rewards. Our findings are the first to show that reward significantly enhanced numerical processing in adolescents with DD, who struggle with mathematics from the early stages of schooling [3] and for whom effective interventions are currently lacking [11,12].

With regards to behavioural performance, our results showed that reward enhances accuracy in both the DD and the TD groups, while slowing down response speed as task difficulty increased. In addition, EZ-diffusion model documented that the drift rate – a measure of information processing efficiency – was the main reward-sensitive component in the DD as well as in the TD controls. Our findings align with previous research demonstrating that TD adults, children and adolescents significantly improved both accuracy and drift rate as well as decreased the speed of response under reward condition compared to no-reward condition [33,57]. The inverse relationship observed between accuracy and speed in our results could be interpreted within the framework proposed by Manohar et al. [58]. The authors suggested that reward may enhance both speed and accuracy by reducing intrinsic neural noise. However, this improvement comes at a cost — the increased cognitive effort needed to exert control. In line with this view, our findings showed that both adolescents with DD and TD controls exhibited higher accuracy and processing efficiency in adolescents with TD and DD under reward condition abut also longer RTs. This pattern may indicate that while reward can indeed enhance perceptual precision, but requires greater control effort in both typical and atypical number processing. In other words, both TD adolescents and those with DD may need to invest greater effort to optimize their performance, possibly reflecting a less efficient or more demanding neural control mechanism [58].

Importantly, understanding of reward effects in individuals with DD is mainly based on results related to number acuity. We showed for the first time that reward significantly enhanced *wf* in TD adolescents and in adolescents with DD, who typically exhibit poor number acuity [44]. The successful development of number acuity – usually referred to as ANS – is critical given its well-established role in predicting later arithmetic achievement in school settings [45,48–54]. Given the importance of ANS for future mathematical abilities, training programs usually aim to enhance number acuity [8]. These interventions either focus on directly improving ANS acuity [5–7] or on refining problem-solving strategies [9] and number sense through mentoring and tutoring[10]. Nevertheless, the overall effectiveness of these interventions in enhancing numerical cognition remains uncertain [8]. In thix context, our study demonstrates that reward-based strategies could serve as an effective boost to enhance basic numerical abilities, complementing the traditional training programs.

Altogether, our results significantly extend prior findings into a clinical population, with twofold accounts. From a neurobiological perspective, although the interaction between the reward system and numerical processing has been scarcely explored [59], some tentative explanations can be proposed. In line with previous findings [33,57], one plausible interpretation of our results is grounded in the *Incentive Salience Hypothesis* [60]. This suggests that reward cues presented at the beginning of a trial enhance the perceptual salience of subsequent stimuli, thereby facilitating their discrimination. In our study, reward may have boosted early visual processing stages of dot clouds in TD adolescents and adolescents with DD, prior to the engagement of the ANS for quantity representation. To better understand the mechanisms underpinning the role of reward in numerosity processing, some previous research combined behavioral performance with pupillometry to measure task-related phasic pupil dilation in TD children and adolescents [33], as well as TD adults [57]. Pupillometry is a sensitive index of arousal, attention and task engagement, commonly used as a non-invasive proxy of locus coeruleus-norepinephrine system activity – known to support attention-related salience networks [61]. In trials where cues predicted a potential reward, participants across age groups (TD children, adolescents, and adults) showed greater pupil dilation compared to trials with neutral cues. The authors suggested that the reward-related enhancement in behavioral performance may result from the interaction between dopaminergic pathways and the locus coeruleus-norepinephrine system [33,57]. Given that our behavioural findings align with those studies, it is plausible to suggest that such dopaminergic–noradrenergic interactions may be functionally preserved in individuals with DD. Although our data are purely behavioural, it can be hypothesized that the observed effects are driven by the engagement of attentive-parietal circuits [40]. Within the reward network, the dorsal portion of the ACC (dACC), which maintains reciprocal connections with the dlPFC, plays a central role in cognitive control and attentional modulation. The dlPFC, through the dACC, exerts top-down influence on subcortical dopaminergic activity and projects back to the striatum, forming a fronto-striatal loop that integrates motivational signals into goal-directed cognitive processes [42]. Through this pathway, reward-based activation may involve the attentive-parietal circuit – which supports and guides goal-directed behaviour towards making decisions [62]. Such activation might enhance parietal areas associated with numerical representation, thereby strengthening the precision of numerosity discrimination during non-symbolic tasks and supporting the decision-making procedures [40].

From a clinical point of view, our findings suggest that the use of reward to boost numerical processing could be a feasible and ease-to-implement strategy in DD adolescents as well as TD adolescents, with potential real-world impact in home or school settings. It is also worth noting that in previous studies, the average value of reward prizes was up to five times higher than in our study —for example, approximately 10 euros for children/adolescents [33] and 20 euros for adults [57], compared to about 2.50 euros in our case. Additionally, participants in previous studies received up to 25 euros for their participation [33,57], which is in itself a strong incentive strategy. In contrast, our study demonstrated that even minimal incentives are sufficient to modulate performance in adolescents with DD and TD – making such an approach more accessible and cost-effective. An additional advantage of our method lies in its successful implementation via remote administration, demonstrating its adaptability across settings. Importantly, the task can be completed independently, with no adult supervision, therefore further enhancing its intrinsic practical application.

Two factors are likely to improve our study further. First incorporating physiological measures, such as pupil diameter, would deepen our understanding of reward-based ANS precision especially in DD, by shedding light on the interaction between reward and number processing systems. The specificity of our finding should also be further explored by adding behavioral tasks testing whether the observed reward effects were specific to numerical processing or may have enhanced more general aspects of cognitive performance.

In conclusion, our findings suggest that low-cost, reward-based interventions can still yield measurable benefits and are therefore practical and feasible. This supports the ecological validity and potential for widespread deployment of similar interventions in school or home settings, especially when resources are limited.

Methods

Participants. A total of 61 neurologically typical adolescents aged 11 to 17 years participated in the study, including 31 with a diagnosis of DD (the DD group) and 30 with TD (the TD group). Four participants were excluded because they did not meet the selection criteria (see Supplementary Analyses). The final sample consisted of 29 TD adolescents (mean age = 13.8, SD=1.6, range = 11.89-17.25 years, 10 females) and 28 adolescents with DD (mean age = 13.9, SD=1.8, range = 11.25-17.67 years, 17 females) for the data analyses.

Based on an a priori power calculation (G*Power, version 3.1.9.7, The G*Power Team, Düsseldorf, Germany), and information from previous studies [33,57], 24 participants (i.e., 12 per group) were required to reach a medium effect size (f) of 0.25, α value = 0.05 (i.e., probability of false positives of 5%), and β = 0.80 (i.e., at least 80% power), in order to perform an analysis of variance (ANOVA) with 2 Groups (typical development vs dyscalculia) and 2 Conditions (rewarded vs unrewarded trials). We planned to test at least 30 adolescents (i.e., 15 per group). Inclusion/exclusion criteria and screening assessments for participant selection are detailed in the Supplementary Methods.

The study was approved by the local ethics committee of the Bambino Gesù Children's Hospital (2501_OPBG_2021) in accordance with the Declaration of Helsinki and performed following the relevant guidelines and regulations. All participants and their parents were fully informed of the procedures and purpose of the experiment and provided written consent prior to participating in the study. Participation was solely voluntary.

After the testing, participants received a voucher for a local stationery store with a value corresponding to the sum they earned during the *monetary-rewarded numerosity discrimination task* (minimum value 2€ and maximum value 5€; a mean value of 2.77 Euro in the DD Group and a mean value of 3.33 Euro in the TD Group).

Figure 1 depicts the study procedures and the experimental paradigm.

Monetary-rewarded numerosity discrimination task. Participants underwent a monetary-rewarded, home-based, remotely administered version of the numerosity discrimination task. This established paradigm is widely used to measure the number acuity, indexed as *wf*, whereby participants typically identify which of two arrays of dots contains more elements [45–47].

The experiment was implemented in Psychopy [63] and was conducted online using the Pavlovia platform for online experiments. The task was divided into two sessions, which were performed on two different days (no more than 48 hours apart). In this task, participants judged which of two sets of dots was the largest using the "Z" and "M" keys of the computer keyboard to indicate whether the set with the larger numerosity was presented on the left or right side of the screen, respectively. Some trials were associated with a reward, some were not (no-reward trials). Participants were informed that they received a monetary reward based on the mean accuracy calculated only on the reward trials (see Supplementary Methods). The trial structure is reported in Figure 1. Before starting each session, participants performed a practice block (32 trials), in which the stimuli were randomly selected from the full stimulus set. This block was performed with the online supervision of the experimenter and was not considered for further analyses.

Each trial started with a fixation point presented at the center of the screen until response or for a maximum of 4500 msec. The reward condition was signaled by the color of the fixation point (red for reward trials and blue for no-reward trials) and by a sound (two different sounds were used, one per condition) synchronized with the onset of the fixation point. After a 1500 msec ISI, the fixation point was followed by two images displaying two sets of dots, presented until response or for a maximum of 1200 msec. The two images were centered at the middle points between the fixation and the left and right borders of the screen. Participants had a maximum of 3000 msec (i.e., 1200 + 1800) from the onset of the dot images to respond. Immediately after the response, accuracy feedback was presented for 1000 msec. The feedback included two elements. An emoticon that reflected the accuracy (smiley emoticon for correct answer, and sad emoticon for incorrect answer or when the participant does not respond within 3000 msec), and a number indicating the score ("2" or "-2" after each correct or incorrect reward trial, and 0 after no-reward trials; see Supplementary Methods). The inter-trial interval consisted of a blank screen presented for 1000 msec, after which the next trial started. All stimuli were displayed on a black background. The dots were presented in white, whereas the fixation point and the score shared the same color based on the reward condition (red for reward trials and blue for no-reward trials). At the end of each block, a screen showing the overall percentage of correct responses was presented.

At the end of the test, participants received a voucher for a local stationery store with a value corresponding to the sum they earned during the monetary-rewarded numerosity discrimination task.

Data analyses. The pre-processing procedures, including outlier exclusion, were reported in the Supplementary Analyses.

Behavioral performance (i.e., accuracy, RTs) and *wf* were considered for analyses. In addition, the EZ-diffusion model [64] was fitted separately for each condition (reward, ratio, and group) and participant. This model estimates three parameters: drift rate (*v*), boundary separation (*a*), and non-decision time (t_{ER}). These parameters are based on the mean and variance of RTs of the correct responses. A detailed description of the method is reported in OSF (add https://osf.io/5sqnt/).

The wf was analyzed with a linear mixed-effects model with maximum-likelihood estimation and participants as random intercepts. The model considered as within-subject effects the factors Reward (i.e., reward vs. control condition), Group (i.e., TD vs. DD), Reward by Group interaction, and Age as a covariate. The model was defined as follows:

wf ~ Reward + Group + Reward:Group + Age + (1 | sj)

Accuracy, RTs, drift rate (*v*), boundary separation (*a*), and non-decision time (t_{ER}) were analyzed with linear mixed-effects models with maximum-likelihood estimation and participants as random intercepts. However, these models included as a within-subject effect also the factor Ratio (i.e., 0.5, 0.75, 0.83, and 0.88). The models were defined as follows:

RTs[1] ~ Reward + Ratio + Group + Reward:Ratio + Reward:Group + Group:Ratio + Reward:Ratio:Group + Age + (1 | sj)

[1] The same formula was used for accuracy, drift rate, boundary separation, and non-decision time.

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Data availability

Raw and processed data will be available in OSF (https://osf.io/5sqnt/).

Declarations

Ethics approval and consent to participate

The studies involving human participants were reviewed and approved by the local research ethics committee (process number 2501_OPBG_2021). Written informed consent to participate in this study was provided by the participants and their families. All the experiments in our study were conducted in accordance to the relevant guidelines and regulations of 1963 Helsinki declaration and its later amendments.

Competing interests

The authors declare no competing interests.

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Figures Legend

Figure 1. Study procedures and experimental paradigm. *Leftmost side:* Participants were first recruited and completed background assessments, including IQ, arithmetic abilities, and emotional and behavioral symptoms, with informed consent obtained (for more information see Supplementary Materials). Twenty-nine typical development (TD) adolescents and twenty-eight adolescents with Developmental Dyscalculia (DD) were included in the sample. *Centre:* During the *numerosity discrimination task*, participants were cued with a colored fixation cross (red cross anticipated reward trials, blue anticipated no-reward trials), followed by two arrays of dots. Participants identified which array contained more dots and received feedback for their performance based on response accuracy (happy/sad emoji and points). Points accumulated during the task were displayed at the end of the experimental task, and translated into monetary rewards, with higher accuracy resulting in greater earnings, as shown in the reward scale on the right side.

Figure 2. Effects of Reward and Group on Accuracy. A: Accuracy distributions across Reward. **B**: Mean Accuracy across Reward. **C**: Accuracy distributions across Group. **D**: Mean Accuracy across Group. Accuracy distributions are presented as a density plot, a boxplot, and a raincloud plot (points represent participants' Accuracy jittered along the x-axis). Asterisks indicate a significant effect ($p < 0.05$).

Figure 3. Effects of Reward, Ratio, and Group on RTs. A: RT distributions across Reward and Ratio. **B**: Mean RTs across Reward and Ratio. **C**: RT distributions across Group and Ratio. **D**: mean RTs across Group and Ratio. RT distributions are presented as a density plot, a boxplot, and a raincloud plot (points represent participants' RTs jittered along the x-axis). Asterisks indicate a significant effect ($p < 0.05$).

Figure 4. Effects of Reward and Group on Weber Fraction (*wf*). A: *wf* distributions across Reward. **B**: mean *wf*s across Reward. **C**: *wf* distributions across Group. **D**: mean *wf*s across Group. *Wf* distributions are presented as a density plot, a boxplot, and a raincloud plot (points represent participants' *wf*s jittered along the x-axis). Asterisks indicate a significant effect ($p < 0.05$).

Figure 5. **Effects of Reward, Ratio, and Group on Drift Rates (DR). A**: DR distributions across Reward. **B**: DRs mean across Reward. **C**: DR distributions across Group and Ratio. **D**: DRs mean across Group and Ratio. DR distributions are presented as a density plot, a

boxplot, and a raincloud plot (points represent participants' DRs jittered along the x-axis). Asterisks indicate significant effects ($p < 0.05$).