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REGISTERED REPORT

The role of intrinsic reward in adolescent word learning

Amrita Bains[1] | Annaliese Barber[1] | Tau Nell[1] | Pablo Ripollés[2,3,4] | Saloni Krishnan[1]

[1]Department of Psychology, Royal Holloway, University of London, Egham Hill, UK

[2]Department of Psychology, New York University, New York, New York, USA

[3]Music and Audio Research Lab (MARL), New York University, New York, New York, USA

[4]Center for Language, Music and Emotion (CLaME), New York University, Max-Planck Institute, New York, New York, USA

Correspondence
Saloni Krishnan, Department of Psychology, Royal Holloway, University of London, Egham Hill TW20 0EX, UK.
Email: saloni.krishnan@rhul.ac.uk

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Abstract

Relatively little work has focused on why we are motivated to learn words. In adults, recent experiments have shown that intrinsic reward signals accompany successful word learning from context. In addition, the experience of reward facilitated long-term memory for words. In adolescence, developmental changes are seen in reward and motivation systems as well as in reading and language systems. Here, in the face of this developmental change, we ask whether adolescents experience reward from word learning, and how the reward and memory benefit seen in adults is modulated by age. We used a naturalistic reading paradigm, which involved extracting novel word meanings from sentence context without the need for explicit feedback. By exploring ratings of enjoyment during the learning phase, as well as recognition memory for words a day later, we assessed whether adolescents show the same reward and learning patterns as adults. We tested 345 children between the ages of 10–18 ($N > 84$ in each 2-year age-band) using this paradigm. We found evidence for our first prediction: children aged 10–18 report greater enjoyment for successful word learning. However, we did not find evidence for age-related change in this developmental period, or memory benefits. This work gives us greater insight into the process of language acquisition and sets the stage for further investigations of intrinsic reward in typical and atypical development.

KEYWORDS
adolescence, hedonia, reward, vocabulary, word learning

Research Highlights

- We constantly learn words from context, even in the absence of explicit rewards or feedback.
- In adults, intrinsic reward experienced during word learning is linked to a dopaminergic circuit in the brain, which also fuels enhancements in memory for words.
- We find adolescents also report enhanced reward or enjoyment when they successfully learn words from sentence context.

Pablo Ripollés and Saloni Krishnan are joint senior authors.

- The relationship between reward and learning is maintained between the ages of 10 and 18.
- Unlike in adults, we did not observe ensuing memory benefits.

1 | INTRODUCTION

From infancy onwards, humans display an innate motivation to acquire language and to communicate. One of the building blocks of the language learning process is the acquisition of new vocabulary (Bloom, 2002). Even young babies can learn new words and their meaning based on a few incidental exposures (Carey & Bartlett, 1978), with little to no explicit feedback. We continue to learn new words over our lifespan, with children learning upwards of 3000 words/year (Anglin et al., 1993). Given this striking capacity for word learning, multiple theories have tried to provide answers to the question of ***how*** humans assign meaning to a word (Carey and Bartlett, 1978; Markman, 1990; McMurray et al., 2012; Smith, 2000; Tomasello, 2003; Kuhl, 2007; Smith et al., 2014). Researchers have also applied these theories to trying to decipher why word learning differs in atypical word learners, such as those with autism and dyslexia (Krishnan et al., 2016; Litt & Nation, 2014; Norbury et al., 2010). In addition, there is a large body of work focusing on how vocabulary learning can be trained and optimized (Bowyer-Crane et al., 2008; Hagen et al., 2017; Krishnan et al., 2017, 2018). Indeed, in the last 20 years word learning has been assessed extensively from different points of view, including memory, attention, and statistical learning (Davis & Gaskell, 2009; de Diego-Balaguer et al., 2016; Rodríguez-Fornells et al., 2009; Saffran et al., 1996). Yet, somewhat surprisingly, there is one cognitive trait whose relationship with word learning processes has received less focus: reward. Focusing on reward, which is such a core aspect of cognition, and exploring its relationship with word learning could shed light on ***why*** humans learn language. Indeed, a recent set of studies in human adults suggested that intrinsic reward signals play an important role in certain types of word learning (Ripollés et al., 2014, 2016, 2018). This work shows that language learning from a written context (i.e., while reading) in human adults, even in absence of explicit feedback, can be its own reward; and that this intrinsic reward facilitates the entrance of new words into long-term memory. This research, although inspired by and aimed at understanding lifespan vocabulary acquisition, currently focuses on adult learning: the interplay between intrinsic reward and language learning has not yet been studied in development. In this study, we fill this gap in the literature by assessing whether intrinsic reward mechanisms also fuel word learning from written context in adolescence (10–18 years).

Adolescence is an important time to understand the interaction between intrinsic reward and language learning systems. Although much work has focused on word learning in early childhood, adolescence is characterized by substantial brain development. Late adolescence (15–18 years) is a particularly sensitive period for learning. In a recent study, Knoll et al. (2016) showed that training older adolescents on relational reasoning and numerosity discrimination tasks yielded the greatest improvements in performance. Although the adults and younger adolescents tested in this study did show training benefits, these were not as pronounced as the gains of the older adolescents. The authors consequently suggested late adolescence might offer a window of opportunity for educational interventions in certain cognitive domains. This peak in learning may be related to developmental changes in reward processing regions of the brain. A recent longitudinal neuroimaging study sampled participants between the ages of 8 and 25 over three biannual measurement waves. They used a task that involved learning categories from feedback, which was previously found to predict future reading and mathematics performance. This study revealed that activity in a core reward-related brain region (the striatum) peaked in late adolescence (Peters & Crone, 2017). Importantly, in this longitudinal study, the authors showed that striatal activity was predictive of later learning performance. The authors argued that increased reward-sensitivity might lead to changes in motivation salience, which in turn would recruit systems that were necessary to boost learning new information. In this vein, we know developmental changes modulate aspects of cognition tied both to language, such as reading (Brown et al., 2005; Church et al., 2008); and to reward processing (van Duijvenvoorde et al., 2016), such as decision making (Blakemore & Robbins, 2012; Hartley & Somerville, 2015; Palminteri et al., 2016; Wolf et al., 2013), and reinforcement learning (Nussebaum & Hartley, 2019; Decker et al., 2016). Neurobiologically, evidence suggests that brain maturation—from childhood to adolescence, and then to adulthood—of cortico-prefrontal and cortico-striatal projections is tightly linked to the behavioral differences found between adolescents and adults in core-cognitive operations closely linked to reward processing (Gee et al., 2018). Given these age-related changes in reward processing systems, and the known link between intrinsic reward and word learning, we expect that reward-related changes over development will exert an influence on word learning behavior. Specifically, we hypothesize that older adolescents will experience the greatest intrinsic reward during learning, given reports suggesting a peak in reward and learning in late adolescence. Additionally, the link between experienced reward and memory will be the strongest in this group.

Changes in reading behavior also mark adolescence. Children become skilled readers between the ages of 10 and 18 (Castles et al., 2018). There are motivational changes in reading—adolescents show a disinclination to read for pleasure, with a particular pressure point being the transition from primary to secondary school (Clark, 2019). This is of significant concern to policy makers, who argue that motivating adolescents to read for pleasure would improve not just literacy outcomes, but also result in substantial economic and societal benefit

(Department for Education, 2015). Some changes might be related to the environment in ways that are currently unexplored. For instance, in primary schools, reading is rewarded explicitly (stickers, praise from teachers etc.). But at secondary school, these explicit rewards are absent, with reading becoming secondary to learning academic content. Our work with young adults suggests that they benefit only minimally from explicit feedback during word learning (Krishnan et al., 2018). This key transition could be managed better by understanding how intrinsic reward mechanisms contribute to word learning during reading.

To understand the relationship between intrinsic reward and word learning, we have adapted an adult word-learning paradigm (Angwin et al., 2019; Mestres-Missé et al., 2007, 2014; Mestres-Missé, et al., 2008; Mestres-Missé, et al., 2008; Ripollés et al., 2014, 2016, 2017, 2018) for use with adolescents. Our paradigm involves learning words from written context (i.e., from reading). Participants can learn the meaning of new words on their own, without external feedback or explicit reward, using the contextual information provided by a duplet of sentences. Following this, participants rate each trial for pleasure, arousal, and confidence. A day later, participants' memory for words they encountered is tested. A strength of this task is that it mimics important aspects of real-word context-based word learning, which is a process that usually occurs without external guidance and is considered one of the sources of vocabulary growth during childhood (6–18 year olds; Nagy et al., 1985). The ecological validity of this task is slightly reduced by making participants reflect on their confidence or reward levels. Yet, previous work (Ripollés et al., 2014, 2016, 2018) has shown that using the same task without the ratings demonstrated clear engagement of the reward system, and only when participants learn new words on their own (the potential of "reverse inference" was reduced by controlling for non-rewarding aspects of stimuli that also engage the reward system, such as novelty and effort). Specifically, in adults, successful extraction of the meaning of new words is associated with intrinsic reward, indexed by subjective ratings of pleasure, and brain activity in reward related regions (Ripollés et al., 2014). Importantly, while subjective ratings involve active reflection about pleasure and may consequently bias the task, the changes in brain activity were noted in the absence of such reflection. Second, subjective ratings of pleasure were not simply reflective of accuracy or confidence. This was assessed by including a condition in which participants can successfully identify that words did not have a meaning. Although confidence was related with accuracy in both these conditions, increases in the pleasure ratings (and increases in ventral striatal activity during the task) were only observed when meaning could be extracted. In addition, we have found memory benefits related to increased reward processing, as indexed by subjective behavioral ratings of hedonia for words that were successfully remembered, neurophysiological responses (skin conductance), and brain activity in a network related to memory, reward and specially dopaminergic signaling (Ripollés et al., 2016 2018). This work clearly shows that non-invasive subjective ratings of pleasantness are a proxy for reward processing in this learning context, and an appropriate predictor of word learning success and memory retention.

On the basis of the work outlined above, **our hypotheses are that a) learning new words while reading will be intrinsically rewarding at an early developmental stage—a hypothesis that has not been tested in children and adolescents—and b) that this intrinsic reward will be related to memory benefits**. In other words, first, we predict that successful word learning will be associated with higher ratings of pleasure in adolescents relative to unsuccessful word learning. To ensure that intrinsic reward is linked to extracting and learning word meaning, and not simply indexing task performance or reading ability, we expect that successful word rejection (i.e., correctly identifying that a word does not have a meaning) will not be associated with higher ratings of pleasure. Second, after a period of consolidation, we predict that accurate memory for learned words will be associated with higher ratings of pleasure during the learning phase. Finally, we also hypothesize that **c) intrinsic reward and word recall will increase with age, peaking in late adolescence**.

One factor that may interact with both reward processing and word learning in adolescence is sleep. Substantial changes in sleep patterns are observed between childhood and adolescence, with adolescents experiencing sleep deprivation due to shifts in their circadian clock and environmental pressures such as early school starts (Baker et al., 2016). Sleep deprivation is linked to unhealthy pursuit of reward. For instance, following just one night of sleep deprivation, late adolescents/young adults showed significantly elevated striatal activity to winning small monetary rewards (Mullin et al., 2013). Sleep also plays a significant role in word learning and consolidation. The dual systems account of word learning posits that replay during sleep leads to the transfer of information from the hippocampus to the cortex (Davis & Gaskell, 2009). This theory has a great deal of empirical support—for instance, an adult fMRI study revealed that newly learned words elicited greater hippocampal activation than words learned the previous day (i.e., with a sleep interval). In contrast, words learned prior to a period of sleep showed increased neocortical activation (Davis et al., 2009). The influence of sleep on the consolidation of words in memory during childhood has also been extensively investigated. These studies reveal that children and adolescents benefit from sleep-related consolidation (James et al., 2020; Knowland et al., 2019; Landi et al., 2018; Smith et al., 2018), and there is evidence suggesting that task, prior knowledge, and reading ability can modulate the benefit provided by sleep (Henderson et al., 2012; James et al., 2017; Landi et al., 2018). Additionally, adult studies demonstrate that sleep does not enhance all memories equally. Rather, the most rewarding memories are prioritized for integration and long-term retention (Fischer & Born, 2009; Igloi et al., 2015). However, relatively little is known about how adolescents learn and consolidate words. Given that our task specifically examines word memory following a period of sleep, we will use a questionnaire to capture sleep quality and duration, which will enable us to assess how these variables interact with both intrinsic reward and memory.

In summary, this study will add to the rich literature on word learning and help us understand the role of intrinsic reward in word learning during development, addressing whether adolescents experience the same "buzz" during learning as adults. In addition, it will showcase how intrinsic reward might influence memory for words during adolescence and highlight how the influence of reward might differ or interact with other known influences on learning and memory, such as sleep and reading ability. Importantly, this work could also help us identify "sensitive" periods in late adolescence (for example, reward-sensitive periods in late adolescence), which could be useful when considering educational policy to boost reading, or for designing interventions focusing on vocabulary learning. It will also provide us with important context for understanding why some children, such as those with dyslexia or developmental language disorder, might struggle with word learning.

2 | METHODS

2.1 | Ethics

This study received approval from the Central Ethics Committee at Royal Holloway, University of London. Informed consent was obtained from parents and assent for those under 18.

2.2 | Participants

We recruited at least 84 participants in each 2-year band between 10 and 18 years of age, that is, 10–12 years ($N = 84$), 12–14 years ($N = 84$) and so on. Our inclusion criteria were native English-speaking children with normal or corrected-to-normal vision. Exclusionary criteria were any known neurological disorder and any speech, language, or hearing disorders. Children and adolescents were recruited via schools and through adverts on social media. Participants who did not complete both parts of the main experiment were replaced by other participants.

2.3 | Stimuli

The stimuli comprised 40 pairs of sentences ending in a novel pseudoword. The pseudoword stood in for a noun. All pseudowords respect the phonotactic rules of English, were between 1 and 2 syllables, 5 and 7 letters in length, and were generated using Wuggy (Keuleers & Brysbaert, 2010). Sentences were validated for use with an adolescent population.

During the experiment, in half of the sentence pairs, the meaning evoked by the pseudoword is congruent and, therefore, it is possible to extract the meaning of the new word (M+ condition; e.g., sentence 1: "Few countries are now ruled by a cyche"; sentence 2: "In the palace lives the king and the cyche." Cyche means *queen* and is congruent with both the first and second sentence). For the other half of the sentence pairs, the second sentences are scrambled so that they no longer match their original first sentences. In this case, the new-word cannot be associated with a congruent meaning across the sentences (M- condition; e.g., sentence 1: "John needed a battery for his bemble." *Watch* is one possible meaning of bemble. Sentence 2: "The teacher wrote the date on the bemble" *Blackboard* is now one of the possible meanings of bemble, which is not congruent with the first sentence). These constitute the M- condition in which meaning acquisition is not possible. The M- condition is used as a control for novelty, task structure and difficulty and cognitive effort (e.g., working memory constrains; see Mestres-Missé et al., 2007, 2014; Ripollés et al., 2014, 2016, 2017, 2018). Sentence assignment to M+ and M- are counterbalanced. In other words, the 20 pairs of sentences that serve as M+ in one version of the experiment are part of the M- condition in the other version.

2.4 | Design

After providing informed consent, participants were told that they would be exposed to new words that we wanted them to learn. Before they started the learning phase, they were informed that they would be tested on their learning on the following day.

During the learning phase on Day 1, participants encountered 40 trials. On each trial of the experiment, participants were shown a screen with the first sentence from a sentence pair and were be prompted to click the next button to continue (making the task self-paced). They then encountered the second sentence of the pair and were prompted to click next to continue. They were asked to enter the meaning of the pseudoword or they could type "reject" to indicate that the two sentences did not have a congruent meaning. After they typed an answer, participants rated their confidence and emotions with respect to arousal and hedonia using 9-point visual scales. For confidence, the scale ranged from a very confused face to a smiling face with a trophy. For hedonia or "enjoyment," the scale ranged from a sad, frowning figure (i.e., very negative) to a happy, smiling figure (i.e., very positive). For arousal, the scale ranged from a tired face (yawning) to a very awake face (see Figure 1). The pairs of M+ and M- sentences were interleaved and presented in a random order. Participants were asked to remember the meaning of the pseudowords or whether they thought that a pseudoword had no meaning attached. No feedback was provided at any point.

Participants also encountered three "catch" trials, interspersed at regular intervals through the learning phase. These specifically instructed the participant to click a specific button, or choose a button related to a category. These were included to make sure participants paid attention and were complying with task instructions.

A recognition test followed a consolidation period of at least 24 h. Participants encountered the pseudowords (for both M+ and M- conditions). Instead of typing in their guess, they were provided with three options (two meanings and the option to reject; as in Ripollés et al., 2014, 2016, 2017, 2018). For the M+ condition, these included the real meaning of the word (correct), a meaning consistent with another pair of sentences presented during the experiment (incorrect), and an option to reject (i.e., to, in the case of an M+, *incorrectly* identify the trial as a non-congruent, M- trial in which meaning cannot be extracted). For the M- condition the options were the meaning evoked by the second sentence just presented before (incorrect), the meaning consistent with another pair of sentences presented during the experiment (incorrect), and an option to reject (i.e., to *correctly* identify the trial as a non-congruent, M- trial in which meaning cannot

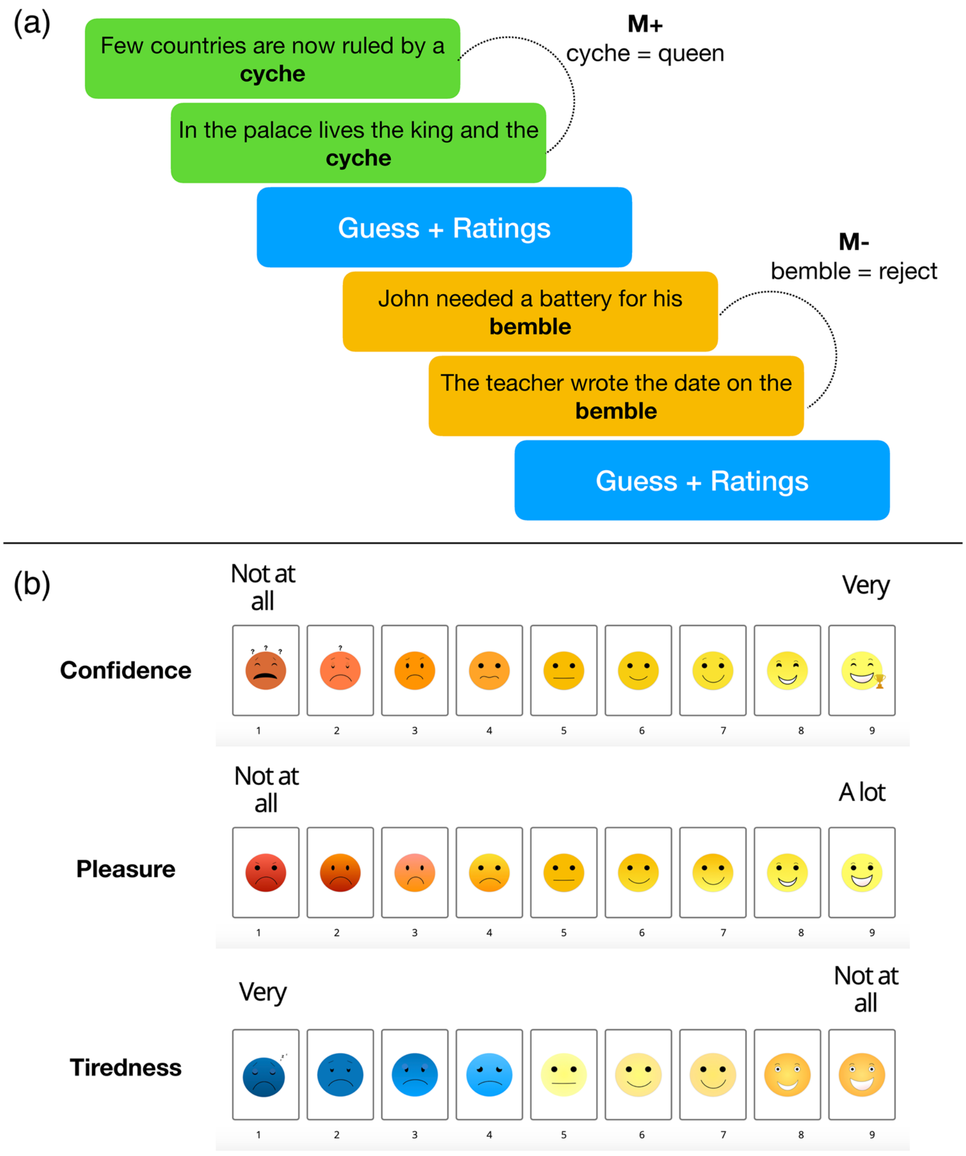

FIGURE 1 Schematic depiction of the learning phase on Day 1, showing representative M+ and M− trials, as well as the pictorial rating scales encountered by participants (color codes in A are for illustrative purposes in this figure; participants see black letters over a white background).

be extracted). After each response, participants rated their confidence using the confidence scale highlighted previously. Participants did not receive feedback on a trial-by-trial basis but were shown a total score at the end.

2.5 | Rating reliability task

To ensure that participants understood the enjoyment rating scales we presented them with, and that these are used similarly across age, we asked participants to complete a short reliability task. Participants encountered 8 statements such as, "You were just complimented on your work," or "It's a hot day, and you have just been given an ice cream," and asked to use the enjoyment scale described above to describe how enjoyable they found the experience. They then encountered the same statement in a second block, and this time they were asked to indicate whether the experience was enjoyable using a yes/no/maybe response (akin to the procedure adopted by Mellor & Moore, 2014). The convergence between the ratings and yes/no/maybe response was assessed in each group to test reliability of ratings. In addition, these also allow us to assess comparability of pleasantness ratings across age groups. We found extremely high reliability, with correlations between the two scales ranging from 0.98 to 0.99 in all age groups.

2.6 | Procedure

Participants completed the experiment online using the Gorilla platform (www.gorilla.sc). After giving informed consent, participants were first given six practice trials with feedback, following which they completed the task (without any feedback). Participants also completed additional short tasks designed to assess their reading ability, that is, an online lexical decision task (Yeatman et al., 2021). Finally, participants completed our short rating reliability task.

At the end of the task, participants were prompted to enter their email addresses, to continue the second part of the experiment the next day. Twenty-four hours later, they were emailed with a link to the second part of the experiment. At the end of the second part of the experiment, participants were asked questions about their sleep—specifically, they were asked to rate how easily they got to sleep the previous night, how well they slept, how easy it was to get up, and how awake they felt in the morning on a 10-point scale (similar to the procedure followed by Smith et al., 2018). They were asked to record what time they went to sleep, and when they woke up. If participants did not complete the entire experiment within 2.5 days, their data were automatically rejected by the experimental platform.

Once participants completed the experiment, we asked parents to fill in a questionnaire that assessed children's sensitivity to reward (Vervoort et al., 2015), as well as the Children's Sleep Habits Questionnaire that assessed sleeping habits (Owens et al., 2000). Parents were emailed a link to these questionnaires.

2.7 | Exclusion criteria

Participants were excluded if they did not complete any of the catch trials accurately. They were also excluded if their learning performance was below 25% for words encountered on Day 1 for M+ trials. Finally, they were excluded if they used a constant score across the enjoyment scales over trials. For the Day 2 memory test, correct answers that had a very low confidence rating were treated as a guess and were not included in the final correct trials.

3 | ANALYSIS

We used an alpha-level of $p < 0.05$ (unless otherwise specified). Our registered analyses used ANOVAs as this type of approach has produced consistent results for this paradigm in adults (Ripollés et al., 2014 2016,2018).

3.1 | Testing registered hypotheses

3.1.1 | Hypothesis 1. Learning new words while reading is intrinsically rewarding early in life and during adolescence

We constructed an omnibus ANOVA on pleasure ratings, with Age Group (4 levels: 10–12; 12–14; 14–16; 16–18 year olds) x Condition (2 levels: M+, M−) x Accuracy during the Day 1 learning phase (2 levels: Correct, Incorrect). We expected to find an Accuracy x Condition interaction (regardless of interaction with age group). We planned to unpack this interaction using paired *t*-tests. We predicted that pleasure ratings would be increased for correct versus incorrect trials in the M+ condition. Further, we expected that pleasure ratings would not differ by accuracy in the M− condition, or alternately, that any difference would be smaller than the change for the M+ condition.

3.1.2 | Hypothesis 2. Intrinsic reward is related to memory benefits

We constructed a second ANOVA on pleasure ratings, this time including the factors Age Group (4 levels: 10–12; 12–14; 14–16; 16–18 year olds) x Condition (2 levels: M+, M−) x Memory (2 levels: Remembered, Forgotten). Memory was calculated on the basis of the 24-h recognition test. We only used the words that were accurately extracted on Day 1 (a recognition rate: the percentage of words recognized on Day 2 from those learned on Day 1; Ripollés et al., 2016 2018). We expected to find a Condition x Memory interaction (independent of age group). Our specific prediction was that hedonic ratings would be higher for remembered than for forgotten M+ new-words. Again, we predicted there would be no difference, or a smaller difference, in the M− condition.

3.1.3 | Hypothesis 3. Intrinsic reward increases with age

We predicted that the difference between hedonic ratings for correct versus incorrect words in the M+ condition would increase with age. We tested this for accuracy with our first omnibus ANOVA, where we expected to find a three-way interaction between Age Group x Condition x Accuracy. To follow up this interaction, we planned to use independent *t*-tests on the difference in pleasure ratings in accurate and inaccurate M+ trials across age group. This would allow us to determine which groups derive the greatest intrinsic reward in this task. We chose this approach as it allowed us to pick up a non-linear change in reward for word learning.

3.2 | Positive controls

We expected to see confidence ratings on Day 1 showing a main effect of accuracy (i.e., children should be more confident about trials they correctly answered). This was tested using a condition x accuracy ANOVA on confidence ratings.

We additionally assessed if overall word learning accuracy during the learning phase was associated with age, predicting that older children will be more accurate in the learning phase. To test this, we ran a correlation between Day 1 accuracy in the M+ condition and age. We expected a significant positive correlation between these two variables.

3.3 | Power analysis

We chose a sample size of 100 participants per group, with a minimum of 84 per 2-year age group in the final sample. This sample size was selected based on several criteria. First, we took into account the sample sizes of our previous studies using a similar paradigm (range: between 29 and 40 participants; Ripollés et al., 2014, 2016, 2018), and

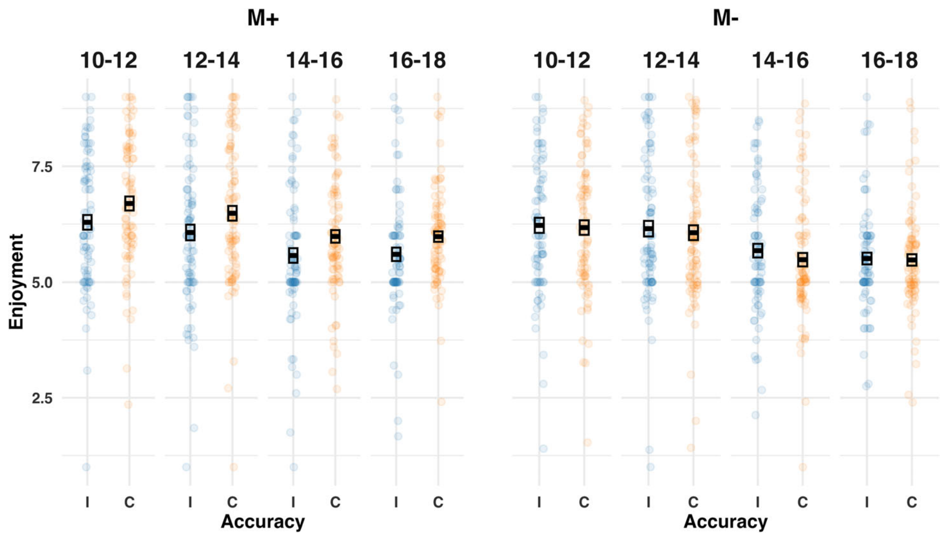

FIGURE 2 Intrinsic reward is greater for successfully extracted words. In the M+ condition, participants in all four age-bands show greater enjoyment when they accurately extract words (C=correct), relative to when they are incorrect (I). In the M− condition, enjoyment is not affected by accuracy. The black boxes show mean ± 1 standard error, the dots behind show data from individual participants.

estimated that we would want at least 40 participants in each age band. We then computed sample size analyses for our hypotheses using the MorePower program (Campbell & Thompson, 2012). To ensure 90% of power to detect significant interactions with a medium size effect (0.06 partial eta^2) at the 5% significance level MorePower estimates indicated that we would need a sample size of greater than 58 participants per group (see Appendix 3, Table S1). For our positive control, we estimated that we would detect a correlation of a medium size effect (r = 0.3) with 90% of power with 110 participants across age groups. Finally, we computed sample size requirements for follow-up t-tests splitting by age group, for our third hypothesis. For independent sample t-tests where a medium effect size (Cohen's $d = 0.5$) is expected and to ensure 90% of power, a sample size in excess of 84 participants in each group is warranted. Due to these different hypotheses, we chose to recruit 100 participants per age group to account for drop-outs, aiming for a minimum final sample of 84 per group (we expected a dropout rate of 10%–20% on day 2 based on our preliminary data). Therefore, we planned to collect data from a total of 400 participants (with a minimum 336 who completed both parts of the experiment), to meet the power requirements.

4 | RESULTS

We retained data from 345 participants. These participants completed both parts of the experiment and passed quality checks.

4.1 | Positive controls

We were able to find strong evidence in support of our two positive controls. First, we observed a significant main effect of accuracy on confidence, $F(1,321) = 238.22$, $p < 0.001$, with children reporting higher confidence on trials where they successfully extracted words (M = 6.8, SD = 1.7), relative to those where they were unsuccessful (M = 5.8, SD = 2.0). Second, we found that overall word learning accuracy during the learning phase was positively associated with age ($r = 0.26$, $p < 0.001$).

4.2 | Testing registered hypotheses

4.2.1 | Hypothesis 1. Learning new words while reading is intrinsically rewarding early in life and during adolescence

Children reported greater enjoyment when they accurately extracted a word, relative to when they did not, $F(1,318) = 40.74$, $p < 0.001$, see Figure 2. We also observed a significant effect of condition, $F(1,318) = 78.36$, $p < 0.001$. This showed children found the M+ trials more enjoyable ($M = 6.10$) than the M− trials ($M = 5.86$). With increasing age, children provided lower enjoyment ratings, $F(3,318) = 6.10$, $p < 0.001$ [10–12, $M = 6.36$; 12–14, $M = 6.23$; 14–16, $M = 5.66$; 16–18, $M = 5.67$], details on interactions are reported below (Hypothesis 3). Importantly, and as predicted, we observed a significant interaction between accuracy and condition, $F(1,318) = 72.54$, $p < 0.001$. As predicted, in the M+ condition, pleasure ratings were higher for correct ($M = 6.31$) versus incorrect trials ($M = 5.89$), $t = 10.07$, $p < 0.0001$. In the M− condition, pleasure ratings were higher in correct ($M = 5.90$) relative to incorrect trials ($M = 5.83$), but this difference did not reach the significance threshold, $t = 1.9$, $p = 0.057$.

4.2.2 | Hypothesis 2. Intrinsic reward is related to memory benefits

Children's pleasure ratings differed by condition, $F(1,302) = 154.18$, $p < 0.001$. Specifically, pleasure ratings for M+ words children learned

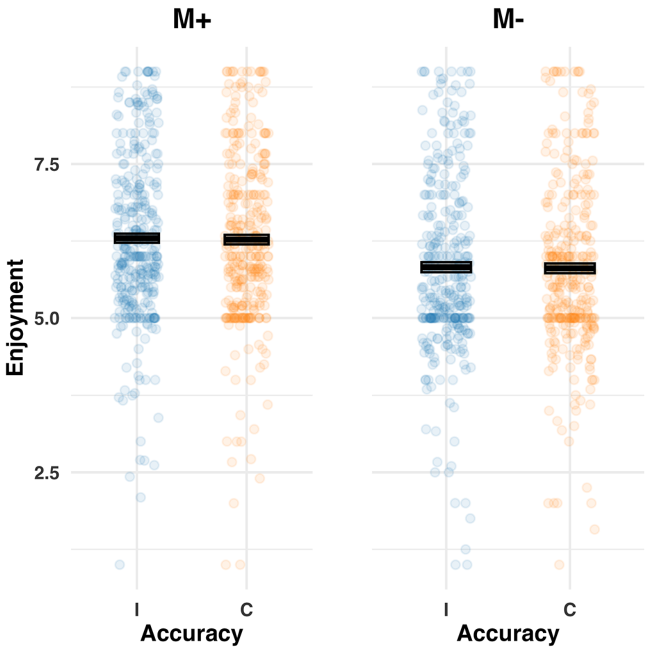

FIGURE 3 Intrinsic reward is not higher for remembered words. In M+ and M− conditions, participants show similar enjoyment when they accurately remember words (C=correct), relative to when they do not (I=Incorrect). The black boxes denote mean ± 1 standard error, the dots behind show data from individual participants.

on day 1 were higher ($M = 6.26$) than for M− words ($M = 5.79$) they correctly rejected on day 1. Again, with increasing age, children showed lower enjoyment ratings, $F(3,302) = 6.34$, $p < 0.001$ [10–12, $M = 6.48$; 12–14, $M = 6.17$; 14–16, $M = 5.76$; 16–18, $M = 5.69$], see Appendix 2, Figure S1. However, contrary to our hypothesis, pleasure ratings did not differ by whether words were remembered ($M = 6.03$) or forgotten ($M = 6.02$). We also did not find evidence for a Condition x Memory interaction, $F(1,302) = 0.00$, $p = 0.99$, see Figure 3.

4.2.3 | Hypothesis 3. Intrinsic reward increases with age

We used the same model as that for Hypothesis 1, but focused on possible interactions with age. We had predicted that the difference between pleasure ratings for correct versus incorrect words in the M+ condition would increase with age. However, we did not find evidence for a three-way interaction between Age Group x Condition x Accuracy, $F(3,318) = 0.72$, $p = 0.54$ (see Figure 2). Rather, our results revealed that in every age group, pleasure ratings were significantly higher for correct versus incorrect trials in the M+ condition [10–12, $t = 5.23$, $p < 0.001$; 12–14, $t = 5.69$, $p < 0.001$; 14–16, $t = 4.85$, $p < 0.001$; 16–18, $t = 4.42$, $p < 0.001$]. In the M- condition, in all groups except 14–16, we did not find significant difference in pleasure ratings [10–12, $t = 0.39$, $p = 0.695$; 12–14, $t = 0.63$, $p = 0.53$; 14–16, $t = 2.89$, $p = 0.004$; 16–18, $t = 0.05$, $p = 0.96$].

4.3 | Exploratory analyses

4.3.1 | The influence of age group and condition on accuracy

Given that this was a developmental sample, we expected to see changes in word learning success by age. We consequently ran an exploratory analysis examining the effects of age and condition (M+/M−) on accuracy. We did not observe a significant main effect of condition, $F(1,341) = 0.55$, $p = 0.46$, Average accuracy for M+ was 0.745 and M− was 0.738. We found that older children were better able to successfully extract words, $F(3,341) = 6.22$, $p < 0.001$ [10–12, $M = 0.73$; 12–14, $M = 0.71$; 14–16, $M = 0.75$; 16–18, $M = 0.79$]. Further, there was a significant interaction between condition and age, $F(3,341) = 3.84$, $p = 0.010$, see Appendix 2, Figure S2. We observed a trend for increasing accuracy over age in the M+ condition, with 16- to 18-year-olds significantly outperforming the 10–12 and 12–14 age groups. However, in the M- condition, there were no significant group differences in performance.

We then explored whether the age-related improvement was maintained over 24h. We ran an exploratory analysis examining the effects of age and condition (M+/ M−) on memory for learned words. There was a significant main effect of condition, $F(1,334) = 40.41$, $p < 0.001$, average accuracy for M+ was 0.391 and M− was 0.510. There was no effect of age group on memory, $F(3,334) = 0.99$, $p = 0.40$, and no significant interaction between condition and age, $F(3,334) = 0.52$, $p = 0.67$.

4.3.2 | Exploring confidence and arousal ratings

In adults, intrinsic reward derives from internal and subjective evaluation of performance, and this subjective evaluation of confidence is associated with learning and memory (Bjork et al., 2013; Ripollés et al., 2016). We therefore explored if confidence ratings were related to condition and accuracy in our developmental sample. We constructed a similar ANOVA to that used for pleasure on the confidence ratings. As predicted, we did find a similar Accuracy x Condition interaction for confidence, $F(3,318) = 83.97$, $p < 0.001$. In the M+ condition, confidence ratings were higher for correct ($M = 6.75$) versus incorrect trials ($M = 5.74$), $t = 16.19$, $p < 0.0001$. In the M− condition, confidence ratings were also higher in correct ($M = 5.87$) relative to incorrect trials ($M = 5.59$), $t = 5.28$, $p < 0.0001$, but this difference was much smaller than the M+ difference. Indeed, confidence ratings were higher in the M+ correct condition relative to any other condition (see Appendix 3, Table S2; this replicates previous work assessing confidence ratings during contextual word-learning in adults; Ripollés et al., 2016).

Our previous studies have shown that arousal is typically not modulated by condition or accuracy (Ripollés et al., 2016, 2018). We therefore included the arousal measure as a control to show that the rating scales are being used meaningfully by participants, and that they tap different aspects of intrinsic emotion. However, we did find a significant effect of Condition x Accuracy on arousal ratings in children,

$F(3,318) = 12.34$, $p < 0.001$. This interaction showed that the M+ condition, arousal ratings were slightly higher for correct ($M = 5.79$) versus incorrect trials ($M = 5.68$), $t = 3.46$, $p = 0.0006$. In the M− condition, arousal ratings were similar in correct ($M = 5.69$) relative to incorrect trials ($M = 5.72$), $t = 1.38$, $p = 0.17$. This might reflect our relatively high sample size, with larger power to detect small effects. The generalized effect sizes were < 0.001 for condition and the interaction between condition and accuracy when considering arousal ratings. By contrast, the generalized effect size for the interaction between condition and accuracy for enjoyment was 0.008.

We expected that the three ratings we collected would give us differential insight into reward, metacognitive, and arousal processes and how they might affect word learning. Given the relative similarity of our findings across these three measures, we assessed the independence of our three ratings by computing correlations between enjoyment, confidence, and arousal for each participant. In our dataset, the average correlation coefficient when correlating enjoyment and confidence ratings was $r = 0.44$, the average correlation coefficient for enjoyment and arousal was $r = 0.29$, and the average correlation between confidence and arousal was $r = 0.21$. The correlation between arousal and enjoyment [10–12: 0.32; 12–14: 0.31; 14–16: 0.30; 16–18: 0.24], $F(3,304) = 1.04$, $p = 0.38$, did not change markedly by age; neither did the correlation between enjoyment and confidence [10–12: 0.43; 12–14: 0.43; 14–16: 0.47; 16–18: 0.45], $F(3,339) = 0.52$, $p = 0.67$; nor did the correlation between confidence and arousal [10–12: 0.23; 12–14: 0.23; 14–16: 0.19; 16–18: 0.18], $F(3,303) = 0.52$, $p = 0.69$.

We then examined whether confidence or arousal affected memory for words on the following day. Confidence ratings from day 1 were marginally higher when words were remembered ($M = 6.34$), relative to when they were forgotten ($M = 6.28$), $t(316) = 1.95$, $p = 0.052$. However, we did not find evidence for a Condition x Memory interaction, $F(1316) = 1.47$, $p = 0.23$. This is in contrast with our previous results in adults (Ripollés et al., 2016), where confidence ratings were higher for M+ correct than for incorrect and for M+ remembered than forgotten words (no differences for M−). This suggests that the group of children tested in this work were less sure of whether they had learned the right word than adults. Arousal ratings did not differ based on whether words were remembered ($M = 5.66$) or forgotten ($M = 5.69$), $t(316) = 1.33$, $p = 0.19$. We did see evidence for a marginal Condition x Memory interaction, $F(1,316) = 2.96$, $p = 0.087$. In the M+ condition where meaning could be extracted, arousal ratings did not differ based on whether words were remembered ($M = 5.72$) or forgotten ($M = 5.72$), $t(316) = 0.30$, $p = 0.77$. In the M− condition, arousal ratings were somewhat higher when words were forgotten ($M = 5.66$) relative to when they were remembered ($M = 5.59$), $t(316) = 1.96$, $p = 0.051$.

4.3.3 | Individual differences

We had planned to conduct exploratory analyses examining individual differences in sensitivity to reward (obtained using a parent filled questionnaire; Vervoort et al., 2015) and aspects of sleep (as assessed by the CSHQ), and how these were correlated with the percentage of learned words during the learning and memory phases. However, despite our best efforts, we received a relatively low return on the parent questionnaires (31.5% of the sample). Given our reduced power, we did not conduct these correlations. These data are openly available on the OSF.

All participants completed the Lexical Decision test and a short sleep questionnaire. Accuracy on the Lexical Decision test was positively associated with word learning success, $r = 0.26$, $p < 0.0001$. However, Lexical Decision test accuracy was not significantly associated with accurately remembering words, $r = 0.01$, $p = 0.4$. Duration of sleep was weakly correlated with initial word learning success, $r = 0.12$, $p = 0.028$, but sleep quality was not associated with word learning success, $r = 0.07$, $p = 0.2$. A stepwise multiple regression with age ($B = 0.02$, $t = 5.0$, $p < 0.0001$), accuracy on lexical decision test ($B = 0.61$, $t = 3.94$, $p < 0.0001$), and duration of sleep ($B = 0.01$, $t = 3.11$, $p < 0.0001$) revealed that all accounted for unique variance (adj $R^2 = 0.1327$, $p < 0.0001$).

We did not find any association between accuracy on the lexical decision task, sleep duration, and sleep quality with memory for learned words.

4.3.4 | Using linear mixed modeling

We also ran additional exploratory analyses using linear mixed modelling in *R* and the *lme4* package. The LMMs allowed us to control for differing numbers of participants in different age groups, and also the possibility that different amounts of data would contribute to different cells of our design (correct/incorrect) across age groups. These results are reported in Appendix 1 and they align with the pattern already presented here.

5 | DISCUSSION

In this study, we investigated the role of intrinsic reward in word learning during development, addressing whether adolescents experience the same "buzz" during learning as adults. We found clear evidence for an increase in pleasure during successful word learning. Although we expected an increase of reward with age, we found that this experience of reward remained fairly stable across the 10–18 year time span. Contrary to our predictions, we did not replicate previous findings in adults of this reward driving memory for words in this sample of adolescents.

This is the first demonstration that successful word learning is associated with the experience of intrinsic reward in *development*. This aligns with our studies on adults (Angwin et al., 2019; Ripollés et al., 2014, 2016; Zaka et al., 2022). Our confidence in our finding that word learning is rewarding in adolescence is increased because of a key control. Our rating reliability task confirmed that children did know to use the enjoyment scale, as they differentially rated sentences of negative affect, and were very reliable across age groups.

So, what makes word learning intrinsically rewarding? In this paradigm, novel words are embedded in language that one can understand. This allows for the generation of predictions, and to test for confirmation of one's prediction, creating optimal conditions for rewarding learning through a balance between familiarity and novelty (Blain & Sharot, 2021). Further, word learning may be adaptive, as word knowledge may be useful in the future. Adults are willing to accept costs to learn the meaning of new words, showing that this is intrinsically valuable (Garvin & Krishnan, 2022). Like adults, children and adolescents feel pleasure when successfully engaging internal learning processes. This may be due to an increase in self-efficacy (Blain & Sharot, 2021), given the increased knowledge, development of agency, confirmation processes, and reduction in anxiety.

Reward may have been driven by both the expansion of knowledge, but also confirmation of a hypothesis. To assess whether our results reflected problem solving or knowledge acquisition, we contrasted performance on the M+ trials where people could learn the meanings of new words, to M− trials, where they could successfully solve the problem but not learn anything new. We were able to show distinctions in the pleasure ratings across M+ and M−, offering an important control for novelty and problem solving. This clearly suggests the experience of successfully extracting word meaning is associated with pleasure. However, younger children found the M− trials confusing. This may have led to them using a strategy of rejecting words. In future studies, including fewer or even no trials of M− may help address this concern, as the increased uncertainty from these trials may affect overall pleasure and learning.

In addition to ratings of pleasure, we also acquired confidence and arousal ratings. In previous studies using this paradigm, we have seen that successful and unsuccessful word learning differentially modulates pleasure and metacognition, while arousal is not associated with word learning performance. Indeed, this might speak to the idea of there being multifaceted aspects to information seeking (Sharot & Sunstein, 2020). Yet, in development, we see some overlap in the patterns of these affective ratings in children, with confidence, arousal and pleasure ratings all showing an interaction between condition and accuracy. This might reflect children use the ratings less systematically, or that these ratings are less separable in development. We consequently examined the relationships between these ratings. As we expected, the interaction between condition and accuracy was strongest for confidence and pleasure (but note adults showed greater differentiation in confidence by condition, suggesting that they were more aware of learning a new M+ word). Additionally, confidence and pleasure ratings were moderately correlated. This likely reflects a true relationship between confidence and pleasure. In the context of this word learning paradigm, people might only experience positive emotional feelings such as pleasure when they are confident about their predictions (Lebreton et al., 2019; Ripollés et al., 2016). This is in line with theories that suggest that intrinsically rewarding activities increase self-efficacy, through processes such as reduction of uncertainty. This is then experienced as a positive feeling and also associated with activity in the reward system (Blain & Sharot, 2021). In contrast to the relationship between confidence and pleasure, we do not find a strong correlation between arousal and enjoyment ratings. This suggests that feelings of pleasure are not driven by arousal, and children can distinguish between pleasure and arousal ratings (Molinaro et al., 2023).

We predicted that there would be age-related increases in the experience of intrinsic reward during word learning. However, our findings suggest that experiencing reward during word learning is a strong and developmentally stable effect. This aligns with recent computational modelling work showing that reward learning rates stay stable across adolescence (Pauli et al., 2023). However, age-related modulations in the subjective value of word learning might be seen in other contexts. For example, adolescents are keenly sensitive to social rewards (Foulkes & Blakemore, 2016). Some word learning contexts might lead to social approval, for example, in second language learning, but also in the speakers' native language: knowing words from a book that everyone is reading, specific words that peers know and denote generational alignment, or knowledge to win a team challenge. Exploring reward for word learning in these social situations could reveal a different developmental trajectory. Age-related changes might also be possible in response to extrinsic rewards for word learning such as better grades or teacher praise. Another possibility is age-related differences might be more apparent when focusing on the motivation to learn (the wanting aspect of reward), rather than in the pleasure of learning (the liking aspect of reward; Berridge & Kringelbach, 2008). In other words, the drive to act or pursue actions that lead to similar rewards may differ (Bains et al., 2023). Adolescents might find word learning equally rewarding but not want to incur costs to pursue such learning. To address these questions, we could ask how much effort are adolescents willing to expend when learning words? Do they want to spend time learning new words? These decisions will greatly affect how much they use and process the learning environment and could underpin changes in reading behavior over adolescence. In other domains, researchers have experimentally manipulated the cost-value to delineate these different aspects of motivation (Chong et al., 2017; Lockwood et al., 2017); similar studies are necessary in the domain of language.

We also did not replicate our effects on the effect of reward on memory. This was surprising given that several studies in adults and in several countries (Australia, Germany, Spain, U.K.) (Angwin et al., 2019; Ripollés et al., 2016, 2018; Zaka et al., 2022), have clearly demonstrated that intrinsic reward can fuel memory. The findings reported here also contrast with a growing literature illustrating the effect of motivational states on learning and memory (Davidow et al., 2016; Fandakova & Gruber, 2021; Garvin & Krishnan, 2022; Gruber et al., 2014). There are several plausible explanations. First, in making this paradigm developmentally appropriate, we simplified the procedure so that presentation of sentence pairs was sequential. This might have contributed to the lack of memory effects, as the level of challenge or effort required to successfully learn words was considerably reduced. This lack of challenge may have reduced enjoyment and subsequently altered the recruitment of memory or cognitive control systems. Indeed, in other work with British adults using the same stimuli with non-sequential presentation, we have been able to show memory effects (Zaka et al., 2022). Non-sequential presentation is actually more naturalistic, for example, words typically occur embedded in different passages of text (Mak et al., 2021). A second and alternate possibility is that children and adolescents are less able than adults to use reward to guide learning, particularly in cognitive demanding environments. For example, previous research shows that adults were able to modify their behavior in a cognitive control task to pursue high-value goals, but adolescents were not able to do so effectively (Insel et al., 2017). The task challenge may have been raised by the inclusion of M— trials in the design, which children found confusing and reduced their confidence in their answers. Indeed, our confidence ratings from day 2 do suggest that children were less aware of when they had learned a word. Future studies reducing the number of words to be learned, as well as removing the M- trials, could help us evaluate this second possibility. A related issue is that lifespan changes in word learning systems, such as stronger consolidation processes in young children (James et al., 2019), might limit our ability to capture smaller effects in memory related to reward. Studies specifically measuring consolidation and reward in our age range could help to disentangle these influences.

We also explored the relationship between sleep quality and duration and word learning. We found a positive association between sleep duration and the probability of word learning success. Although we did not predict this, this may reflect better sleepers being better at word learning. Indeed, we also found that those who performed better on the lexical decision test were also more successful at initially learning words, potentially reflecting individual differences in language and literacy ability. However, we did not find that overall sleep quality or duration predicted memory for words. This likely reflects the relative simplicity of our sleep-based questionnaires, but there is also emerging evidence that sleep may not affect recognition measures in the same way (Newbury et al., 2021).

It is important to note some broad limitations and future directions for this work. First, although contextual word learning is a powerful and naturalistic way in which we learn words (Nagy et al., 1985; Nation, 2017; Nelson, 2008), asking participants to report their enjoyment following learning might change their experience. Note, however, that contextual word-learning in adults increases brain activity in core reward-related regions even when not directly asking about enjoyment (Ripollés et al., 2014). Asking children to perform the task while taking other measures (for example, fMRI to detect brain activity in the ventral striatum; Ripollés et al., 2014, or skin conductance responses; 2016) could offer important converging evidence while limiting biases related to self-reports. Second, in this study, we focused on recruiting neurotypical children to establish age-related changes. However, this does not help us determine how skill and knowledge might affect enjoyment. In future studies, we intend to investigate how task difficulty or children's reading and language skill can interact with the experience of reward. Finally, our intention was not to investigate whether this experience of reward is specific to language. Rather, we argue that this powerful domain-general reward system is recruited during language learning. In future work, we could ascertain how specific this effect might be to word learning, or whether it is experienced in other contexts (e.g., perceptual learning; Kizilirmak et al., 2016).

In conclusion, we find that word learning is pleasurable for children and adults. This is an important finding as it will ultimately allow us to develop strategies to drive engagement with language and reading, optimizing learning experiences in childhood. Interestingly, we observed that the experience of reward was a stable effect across the ages of 10–18, with little evidence for modulation by age. Surprisingly, we did not find expected links between reward-memory, and this remains an open question for future research.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicting interests to declare.

DATA AVAILABILITY STATEMENT

Anonymized data and code is openly available on the Open Science Framework (https://osf.io/p598t/).

ORCID

Saloni Krishnan https://orcid.org/0000-0002-6466-141X

REFERENCES

Anglin, J. M., Miller, G. A., & Wakefield, P. C. (1993). Vocabulary development: A morphological analysis. *Monographs of the Society for Research in Child Development*, *58*(10), i–186. JSTOR. https://doi.org/10.2307/1166112

Angwin, A. J., Wilson, W. J., Ripollés, P., Rodriguez-Fornells, A., Arnott, W. L., Barry, R. J., Cheng, B. B. Y., Garden, K., & Copland, D. A. (2019). White noise facilitates new-word learning from context. *Brain and Language*, *199*, 104699. https://doi.org/10.1016/j.bandl.2019.104699

Bains, A., Spaulding, C., Ricketts, J., & Krishnan, S. (2023). Using a willingness to wait design to assess how readers value text. *Npj Science of Learning*, *8*(1), 17. https://doi.org/10.1038/s41539-023-00160-3

Baker, F. C., Willoughby, A. R., de Massimiliano, Z., Franzen, P. L., Prouty, D., Javitz, H., Hasler, B., Clark, D. B., & Colrain, I. M. (2016). Age-related differences in sleep architecture and electroencephalogram in adolescents in the national consortium on alcohol and neurodevelopment in adolescence sample. *Sleep*, *39*(7), 1429–1439. https://doi.org/10.5665/sleep.5978

Berridge, K. C., & Kringelbach, M. L. (2008). Affective neuroscience of pleasure: Reward in humans and animals. *Psychopharmacology*, *199*(3), 457–480. https://doi.org/10.1007/s00213-008-1099-6

Bjork, R. A., Dunlosky, J., & Kornell, N. (2013). Self-regulated learning: Beliefs, techniques, and illusions. *Annual Review of Psychology*, *64*(1), 417–444. https://doi.org/10.1146/annurev-psych-113011-143823

Blain, B., & Sharot, T. (2021). Intrinsic reward: Potential cognitive and neural mechanisms. *Current Opinion in Behavioral Sciences*, *39*, 113–118. https://doi.org/10.1016/j.cobeha.2021.03.008

Blakemore, S.-J., & Robbins, T. W. (2012). Decision-making in the adolescent brain. *Nature Neuroscience*, *15*(9), 1184–1191. https://doi.org/10.1038/nn.3177

Bloom, P. (2002). *How children learn the meanings of words*. MIT press.

Bowyer-Crane, C., Snowling, M. J., Duff, F. J., Fieldsend, E., Carroll, J. M., Miles, J., Götz, K., & Hulme, C. (2008). Improving early language and literacy skills: Differential effects of an oral language versus a phonology with reading intervention. *Journal of Child Psychology and Psychiatry*, *49*(4), 422–432. https://doi.org/10.1111/j.1469-7610.2007.01849.x

Brown, T. T., Lugar, H. M., Coalson, R. S., Miezin, F. M., Petersen, S. E., & Schlaggar, B. L. (2005). Developmental changes in human cerebral functional organization for word generation. *Cerebral Cortex*, *15*(3), 275–290. https://doi.org/10.1093/cercor/bhh129

Campbell, J. I. D., & Thompson, V. A. (2012). MorePower 6.0 for ANOVA with relational confidence intervals and Bayesian analysis. *Behavior Research Methods*, *44*(4), 1255–1265. https://doi.org/10.3758/s13428-012-0186-0

Carey, S., & Bartlett, E. (1978). Acquiring a Single New Word.

Castles, A., Rastle, K., & Nation, K. (2018). Ending the reading wars: Reading acquisition from novice to expert. *Psychological Science in the Public Interest*, *19*(1), 5–51. https://doi.org/10.1177/1529100618772271

Chong, T. T.-J., Apps, M., Giehl, K., Sillence, A., Grima, L. L., & Husain, M. (2017). Neurocomputational mechanisms underlying subjective valuation of effort costs. *PLoS Biology*, *15*(2), e1002598. https://doi.org/10.1371/journal.pbio.1002598

Church, J. A., Coalson, R. S., Lugar, H. M., Petersen, S. E., & Schlaggar, B. L. (2008). A developmental fMRI study of reading and repetition reveals changes in phonological and visual mechanisms over age. *Cerebral Cortex*, *18*(9), 2054–2065. https://doi.org/10.1093/cercor/bhm228

Clark, C. (2019). *Children and young people's reading in 2017/18* (p. 18). National Literacy Trust.

Davidow, J. Y., Foerde, K., Galván, A., & Shohamy, D. (2016). An upside to reward sensitivity: The hippocampus supports enhanced reinforcement learning in adolescence. *Neuron*, *92*(1), 93–99. https://doi.org/10.1016/j.neuron.2016.08.031

Davis, M. H., Di Betta, A. M., Macdonald, M. J. E., & Gaskell, M. G. (2009). Learning and consolidation of novel spoken words. *Journal of Cognitive Neuroscience*, *21*(4), 803–820. https://doi.org/10.1162/jocn.2009.21059

Davis, M. H., & Gaskell, M. G. (2009). A complementary systems account of word learning: Neural and behavioural evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1536), 3773–3800. https://doi.org/10.1098/rstb.2009.0111

Decker, J. H., Otto, A. R., Daw, N. D., & Hartley, C. A. (2016). From creatures of habit to goal-directed learners: Tracking the developmental emergence of model-based reinforcement learning. *Psychological Science*, *27*(6), 848–858.

de Diego-Balaguer, R., Martinez-Alvarez, A., & Pons, F. (2016). Temporal attention as a scaffold for language development. *Frontiers in Psychology*, *7*, https://doi.org/10.3389/fpsyg.2016.00044

Department for Education. (2015). *Reading: The next steps. Supporting higher standards in schools* (DFE-00094-2015). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/409409/Reading_the_next_steps.pdf

Fandakova, Y., & Gruber, M. J. (2021). States of curiosity and interest enhance memory differently in adolescents and in children. *Developmental Science*, *24*(1), e13005. https://doi.org/10.1111/desc.13005

Fischer, S., & Born, J. (2009). Anticipated reward enhances offline learning during sleep. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *35*(6), 1586–1593. https://doi.org/10.1037/a0017256

Foulkes, L., & Blakemore, S.-J. (2016). Is there heightened sensitivity to social reward in adolescence? *Current Opinion in Neurobiology*, *40*, 81–85. https://doi.org/10.1016/j.conb.2016.06.016

Garvin, B., & Krishnan, S. (2022). Curiosity-driven learning in adults with and without dyslexia. *Quarterly Journal of Experimental Psychology*, *75*(1), 156–168. https://doi.org/10.1177/17470218211037474

Gee, D. G., Bath, K. G., Johnson, C. M., Meyer, H. C., Murty, V. P., Bos, W. van den, & Hartley, C. A. (2018). Neurocognitive development of motivated behavior: Dynamic changes across childhood and adolescence. *Journal of Neuroscience*, *38*(44), 9433–9445. https://doi.org/10.1523/JNEUROSCI.1674-18.2018

Gruber, M. J., Gelman, B. D., & Ranganath, C. (2014). States of curiosity modulate hippocampus-dependent learning via the dopaminergic circuit. *Neuron*, *84*(2), 486–496. https://doi.org/10.1016/j.neuron.2014.08.060

Hagen, Å. M., Melby-Lervåg, M., & Lervåg, A. (2017). Improving language comprehension in preschool children with language difficulties: A cluster randomized trial. *Journal of Child Psychology and Psychiatry*, *58*(10), 1132–1140. https://doi.org/10.1111/jcpp.12762

Hartley, C. A., & Somerville, L. H. (2015). The neuroscience of adolescent decision-making. *Current Opinion in Behavioral Sciences*, *5*, 108–115. https://doi.org/10.1016/j.cobeha.2015.09.004

Henderson, L. M., Weighall, A. R., Brown, H., & Gaskell, M. G. (2012). Consolidation of vocabulary is associated with sleep in children. *Developmental Science*, *15*(5), 674–687. https://doi.org/10.1111/j.1467-7687.2012.01172.x

Igloi, K., Gaggioni, G., Sterpenich, V., & Schwartz, S. (2015). A nap to recap or how reward regulates hippocampal-prefrontal memory networks during daytime sleep in humans. *eLife*, *4*, e07903. https://doi.org/10.7554/eLife.07903

Insel, C., Kastman, E. K., Glenn, C. R., & Somerville, L. H. (2017). Development of corticostriatal connectivity constrains goal-directed behavior during adolescence. *Nature Communications*, *8*(1), 1605. https://doi.org/10.1038/s41467-017-01369-8

James, E., Gaskell, M. G., & Henderson, L. M. (2019). Offline consolidation supersedes prior knowledge benefits in children's (but not adults') word learning. *Developmental Science*, *22*(3), e12776. https://doi.org/10.1111/desc.12776

James, E., Gaskell, M. G., & Henderson, L. M. (2020). Sleep-dependent consolidation in children with comprehension and vocabulary weaknesses: It'll be alright on the night? *Journal of Child Psychology and Psychiatry*, *61*(10), 1104–1115. https://doi.org/10.1111/jcpp.13253

James, E., Gaskell, M. G., Weighall, A., & Henderson, L. (2017). Consolidation of vocabulary during sleep: The rich get richer? *Neuroscience & Biobehavioral Reviews*, *77*, 1–13. https://doi.org/10.1016/j.neubiorev.2017.01.054

Keuleers, E., & Brysbaert, M. (2010). Wuggy: A multilingual pseudoword generator. *Behavior Research Methods*, *42*(3), 627–633. https://doi.org/10.3758/BRM.42.3.627

Kizilirmak, J. M., Galvao Gomes da Silva, J., Imamoglu, F., & Richardson-Klavehn, A. (2016). Generation and the subjective feeling of "aha!" are independently related to learning from insight. *Psychological Research*, *80*(6), 1059–1074. https://doi.org/10.1007/s00426-015-0697-2

Knoll, L. J., Fuhrmann, D., Sakhardande, A. L., Stamp, F., Speekenbrink, M., & Blakemore, S.-J. (2016). A window of opportunity for cognitive training in adolescence. *Psychological Science*, *27*(12), 1620–1631. https://doi.org/10.1177/0956797616671327

Knowland, V. C. P., Fletcher, F., Henderson, L.-M., Walker, S., Norbury, C. F., & Gaskell, G. (2019). Sleep promotes phonological learning in children across language and autism spectra. *Journal of Speech, Language, and Hearing Research*, *62*(12), 4235–4255. https://doi.org/10.1044/2019_JSLHR-S-19-0098

Krishnan, S., Sellars, E., Wood, H., Bishop, Dorothy V. M., & Watkins, Kate E. (2018). The influence of evaluative right/wrong feedback on phonological and semantic processes in word learning. *Royal Society Open Science*, *5*(9), 171496. https://doi.org/10.1098/rsos.171496

Krishnan, S., Watkins, K. E., & Bishop, D. V. M. (2016). Neurobiological basis of language learning difficulties. *Trends in Cognitive Sciences*, *20*(9), 701–714. https://doi.org/10.1016/j.tics.2016.06.012

Krishnan, S., Watkins, K. E., & Bishop, D. V. M. (2017). The effect of recall, reproduction, and restudy on word learning: A pre-registered study. *BMC Psychology*, *5*, 28. https://doi.org/10.1186/s40359-017-0198-8

Kuhl, P. K. (2007). Is speech learning 'gated' by the social brain? *Developmental Science*, *10*(1), 110–120.

Landi, N., Malins, J. G., Frost, S. J., Magnuson, J. S., Molfese, P., Ryherd, K., Rueckl, J. G., Mencl, W. E., & Pugh, K. R. (2018). Neural representations for newly learned words are modulated by overnight consolidation, reading skill, and age. *Neuropsychologia*, *111*, 133–144. https://doi.org/10.1016/j.neuropsychologia.2018.01.011

Lebreton, M., Bacily, K., Palminteri, S., & Engelmann, J. B. (2019). Contextual influence on confidence judgments in human reinforcement learning. *PLoS Computational Biology*, *15*(4), e1006973. https://doi.org/10.1371/journal.pcbi.1006973

Litt, R. A., & Nation, K. (2014). The nature and specificity of paired associate learning deficits in children with dyslexia. *Journal of Memory and Language*, *71*(1), 71–88. https://doi.org/10.1016/j.jml.2013.10.005

Lockwood, P. L., Hamonet, M., Zhang, S. H., Ratnavel, A., Salmony, F. U., Husain, M., & Apps, M. A. J. (2017). Prosocial apathy for helping others when effort is required. *Nature Human Behaviour*, *1*(7), 0131. https://doi.org/10.1038/s41562-017-0131

Mak, M. H. C., Hsiao, Y., & Nation, K. (2021). Anchoring and contextual variation in the early stages of incidental word learning during reading. *Journal of Memory and Language*, *118*, 104203. https://doi.org/10.1016/j.jml.2020.104203

McMurray, B., Horst, J. S., & Samuelson, L. K. (2012). Word learning emerges from the interaction of online referent selection and slow associative learning. *Psychological Review*, *119*(4), 831–877.

Mellor, D., & Moore, K. A. (2014). The use of likert scales with children. *Journal of Pediatric Psychology*, *39*(3), 369–379. https://doi.org/10.1093/jpepsy/jst079

Mestres-Missé, A., Càmara, E., Rodriguez-Fornells, A., Rotte, M., & Münte, T. F. (2008). Functional neuroanatomy of meaning acquisition from context. *Journal of Cognitive Neuroscience*, *20*(12), 2153–2166. https://doi.org/10.1162/jocn.2008.20150

Mestres-Missé, A., Münte, T. F., & Rodriguez-Fornells, A. (2008). Functional neuroanatomy of contextual acquisition of concrete and abstract words. *Journal of Cognitive Neuroscience*, *21*(11), 2154–2171. https://doi.org/10.1162/jocn.2008.21171

Mestres-Missé, A., Münte, T. F., & Rodriguez-Fornells, A. (2014). Mapping concrete and abstract meanings to new words using verbal contexts. *Second Language Research*, *30*(2), 191–223. https://doi.org/10.1177/0267658313512668

Mestres-Missé, A., Rodriguez-Fornells, A., & Münte, T. F. (2007). Watching the brain during meaning acquisition. *Cerebral Cortex*, *17*(8), 1858–1866. https://doi.org/10.1093/cercor/bhl094

Molinaro, G., Cogliati Dezza, I., Bühler, S. K., Moutsiana, C., & Sharot, T. (2023). Multifaceted information-seeking motives in children. *Nature Communications*, *14*(1), 5505. https://doi.org/10.1038/s41467-023-40971-x

Mullin, B. C., Phillips, M. L., Siegle, G. J., Buysse, D. J., Forbes, E. E., & Franzen, P. L. (2013). Sleep deprivation amplifies striatal activation to monetary reward. *Psychological Medicine*, *43*(10), 2215–2225. https://doi.org/10.1017/S0033291712002875

Nagy, W. E., Herman, P. A., & Anderson, R. C. (1985). Learning words from context. *Reading Research Quarterly*, *20*(2), 233–253. JSTOR. https://doi.org/10.2307/747758

Nation, K. (2017). Nurturing a lexical legacy: Reading experience is critical for the development of word reading skill. *Npj Science of Learning*, *2*(1), 3. https://doi.org/10.1038/s41539-017-0004-7

Nelson, D. L. (2008). A context-based strategy for teaching vocabulary. *The English Journal*, *97*(4), 33–37.

Newbury, C. R., Crowley, R., Rastle, K., & Tamminen, J. (2021). Sleep deprivation and memory: Meta-analytic reviews of studies on sleep deprivation before and after learning. *Psychological Bulletin*, *147*(11), 1215–1240. https://doi.org/10.1037/bul0000348

Norbury, C. F., Griffiths, H., & Nation, K. (2010). Sound before meaning: Word learning in autistic disorders. *Neuropsychologia*, *48*(14), 4012–4019. https://doi.org/10.1016/j.neuropsychologia.2010.10.015

Nussenbaum, K., & Hartley, C. A. (2019). Reinforcement learning across development: What insights can we draw from a decade of research? *Developmental Cognitive Neuroscience*, *40*, 100733.

Owens, J. A., Spirito, A., & McGuinn, M. (2000). The Children's Sleep Habits Questionnaire (CSHQ): Psychometric properties of a survey instrument for school-aged children. *Sleep*, *23*(8), 1–9. https://doi.org/10.1093/sleep/23.8.1d

Palminteri, S., Kilford, E. J., Coricelli, G., & Blakemore, S.-J. (2016). The computational development of reinforcement learning during adolescence. *PLoS Computational Biology*, *12*(6), e1004953. https://doi.org/10.1371/journal.pcbi.1004953

Pauli, R., Brazil, I. A., Kohls, G., Klein-Flügge, M. C., Rogers, J. C., Dikeos, D., Dochnal, R., Fairchild, G., Fernández-Rivas, A., Herpertz-Dahlmann, B., Hervas, A., Konrad, K., Popma, A., Stadler, C., Freitag, C. M., De Brito, S. A., & Lockwood, P. L. (2023). Action initiation and punishment learning differ from childhood to adolescence while reward learning remains stable. *Nature Communications*, *14*(1), 5689. https://doi.org/10.1038/s41467-023-41124-w

Peters, S., & Crone, E. A. (2017). Increased striatal activity in adolescence benefits learning. *Nature Communications*, *8*(1), 1983. https://doi.org/10.1038/s41467-017-02174-z

Ripollés, P., Biel, D., Peñaloza, C., Kaufmann, J., Marco-Pallarés, J., Noesselt, T., & Rodríguez-Fornells, A. (2017). Strength of temporal white matter pathways predicts semantic learning. *Journal of Neuroscience*, *37*(46), 11101–11113. https://doi.org/10.1523/JNEUROSCI.1720-17.2017

Ripollés, P., Ferreri, L., Mas-Herrero, E., Alicart, H., Gómez-Andrés, A., Marco-Pallares, J., Antonijoan, R. M., Noesselt, T., Valle, M., Riba, J., & Rodriguez-Fornells, A. (2018). Intrinsically regulated learning is modulated by synaptic dopamine signaling. *eLife*, *7*, e38113. https://doi.org/10.7554/eLife.38113

Ripollés, P., Marco-Pallarés, J., Alicart, H., Tempelmann, C., Rodríguez-Fornells, A., & Noesselt, T. (2016). Intrinsic monitoring of learning success facilitates memory encoding via the activation of the SN/VTA-Hippocampal loop. *eLife*, *5*, e17441. https://doi.org/10.7554/eLife.17441

Ripollés, P., Marco-Pallarés, J., Hielscher, U., Mestres-Missé, A., Tempelmann, C., Heinze, H.-J., Rodríguez-Fornells, A., & Noesselt, T. (2014). The role of reward in word learning and its implications for language acquisition. *Current Biology*, *24*(21), 2606–2611. https://doi.org/10.1016/j.cub.2014.09.044

Rodríguez-Fornells, A., Cunillera, T., Mestres-Missé, A., & de Diego-Balaguer, R. (2009). Neurophysiological mechanisms involved in language learning in adults. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1536), 3711–3735. https://doi.org/10.1098/rstb.2009.0130

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, *274*(5294), 1926–1928. https://doi.org/10.1126/science.274.5294.1926

Sharot, T., & Sunstein, C. R. (2020). How people decide what they want to know. *Nature Human Behaviour*, *4*(1), 14–19. https://doi.org/10.1038/s41562-019-0793-1

Smith, L. B. (2000). Learning how to learn words. *Becoming a word learner: A debate on lexical acquisition*. Oxford University Press.

Smith, F. R. H., Gaskell, M. G., Weighall, A. R., Warmington, M., Reid, A. M., & Henderson, L. M. (2018). Consolidation of vocabulary is associated with sleep in typically developing children, but not in children with dyslexia. *Developmental Science*, *21*(5), e12639. https://doi.org/10.1111/desc.12639

Smith, L. B., Suanda, S. H., & Yu, C. (2014). The unrealized promise of infant statistical word-referent learning. *Trends in Cognitive Sciences*, *18*(5), 251–258.

Tomasello, M. (2003). The key is social cognition. In D. Gentner & S. Goldin-Meadow (Eds.), *Language in mind: Advances in the study of language and thought* (pp. 47–57). Boston Review.

van Duijvenvoorde, A. C. K., Peters, S., Braams, B. R., & Crone, E. A. (2016). What motivates adolescents? Neural responses to rewards and their influence on adolescents' risk taking, learning, and cognitive control. *Neuroscience & Biobehavioral Reviews*, *70*, 135–147. https://doi.org/10.1016/j.neubiorev.2016.06.037

Vervoort, L., Vandeweghe, L., Vandewalle, J., Van Durme, K., Vandevivere, E., Wante, L., McIntosh, K., Verbeken, S., Moens, E., Goossens, L., & Braet, C. (2015). Measuring Punishment and Reward Sensitivity in children and adolescents with a parent-report version of the Bis/Bas-scales. *Personality and Individual Differences*, *87*, 272–277. https://doi.org/10.1016/j.paid.2015.08.024

Wolf, L. K., Wright, N. D., Kilford, E. J., Dolan, R. J., & Blakemore, S.-J. (2013). Developmental changes in effects of risk and valence on adolescent decision-making. *Cognitive Development*, *28*(3), 290–299. https://doi.org/10.1016/j.cogdev.2013.04.001

Yeatman, J. D., Tang, K. A., Donnelly, P. M., Yablonski, M., Ramamurthy, M., Karipidis, I. I., Caffarra, S., Takada, M. E., Kanopka, K., Ben-Shachar, M., & Domingue, B. W. (2021). Rapid online assessment of reading ability. *Scientific Reports*, *11*, 6396. https://doi.org/10.1038/s41598-021-85907-x

Zaka, H., Selvarajah, B., Evans, S., Ripolles, P., & Krishnan, S. (2022). *The influence of intrinsic reward on word learning in oral and written contexts* [Preprint]. PsyArXiv. https://doi.org/10.31234/osf.io/5kswr

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