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Age-related differences in expectation-based novel word learning

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Abstract

Adult language users can infer the meaning of a previously unfamiliar word from a single exposure to this word in a semantically and thematically constrained context, henceforth, predictive context (Borovsky et al., 2010 *Cognition*, *116*(2), 289–296; Borovsky et al., 2012 *Language Learning and Development*, *8*(3), 278–302). Children use predictive contexts to anticipate upcoming stimuli (Borovsky et al., 2012 *Language Learning and Development*, *8*(3), 278–302; Mani & Huettig, 2012 *Journal of Experimental Psychology: Human Perception and Performance*, *38*(4), 843–847), but the extent to which they rely on prediction to learn novel word forms is unclear (Gambi et al., 2021 *Cognition*, *211*, 104650). Here, we examine children's one-shot learning from predictive contexts using a modified version of the one-shot learning ERP paradigm for children aged 7–13 years. In a first learning phase, we presented audio recordings of expected words and unexpected novel pseudowords in strongly and weakly constraining sentence contexts. In the following priming phase, the same recorded words and pseudowords were used as primes to identical/synonymous, related, and unrelated target words. We measured N400 modulations to the word and pseudoword continuations in the learning phase and to the identical/synonymous, related, or unrelated target words in the priming phase. When initially presented in strongly constraining sentences, novel pseudowords primed synonymous targets equally well as word primes of the same intended meaning. This pattern was particularly pronounced in older children. Our findings suggest that, around early adolescence, children can use single exposures to constraining contexts to infer the meaning of novel words and to integrate these novel words in their lexicons.

KEYWORDS

ERP, language development, N400, one-shot learning, prediction, semantic priming, sentential constraint

1 | INTRODUCTION

Prediction, or the effective use of context to anticipate incoming information, is a ubiquitous language processing strategy for adults (Chang et al., 2006; Kutas et al., 2011; Pickering & Gambi, 2018; Pickering & Garrod, 2013). When supported by previous sentential context, expected words are read faster (Smith & Levy, 2013), recognized easier (Brothers et al., 2015; Stites et al., 2017), accessed easier (Kutas et al., 2011), corrected easier in case of small imperfections (Kim & Lai, 2012), and encoded in memory more efficiently (Höltje et al., 2019). Predictive processing facilitates adult language comprehension as listeners and readers use the sentential context to actively construct and continuously update their internal expectations of upcoming meanings (Federmeier, 2007; Gambi et al., 2018; Kutas et al., 2011; Mani et al., 2016).

When it comes to language learning, predictive processing takes time to develop and is closely related to age and linguistic experience (Bion et al., 2013; Borovsky, Elman, & Fernald, 2012; Mani & Huettig, 2012). Furthermore, it is still unclear how likely young comprehenders are to use prediction to map meanings to novel word forms, or how much experience with language they need to have in order to do so (Huettig & Mani, 2016; Rabagliati et al., 2016).

Unlike children, adult readers and listeners have been shown to readily use context-based predictive processing to learn novel word forms. Adults reading pseudowords in short discourses could associate the novel word forms with the expected meanings after 10 exposures during an explicit learning task and later showed indications of implicit lexical consolidation in memory (Batterink & Neville, 2011). Similarly, adult learners were able to use strongly constraining contexts to correctly generate synonyms of unfamiliar rare words (Frishkoff et al., 2010). Moreover, 2 days after being given three exposures to these words in strongly constraining contexts, the same participants showed indications of long-term semantic associations between the learned rare words and their synonyms (Frishkoff et al., 2010).

Even with a single learning opportunity, adults can use strongly constraining sentential contexts to generate predictions about the meaning of previously unencountered pseudowords (Borovsky et al., 2010; Borovsky, Elman, & Kutas, 2012). Borovsky et al. (2010) demonstrated young adults' one-shot learning abilities by presenting novel pseudowords in sentential contexts that constrained toward either a single continuation (high or strong constraint) or allowed for many other completions (low or weak constraint). Strongly constraining sentences such as "He tried to put the pieces of the broken plate back together with…" allowed participants to match the expected meaning (glue) to the presented novel word MARF. Conversely, low constraint sentences such as "She walked across the room to Mike's messy desk to return his…" afforded no specific meanings to attach to the novel word MARF, leaving participants with few clues as to what it might mean. The learning phase was followed by a second phase aimed to examine how well the novel meanings were retained. Instead of explicitly asking participants what they believed MARF meant, Borovsky et al. (2010) tested their implicit knowledge of the novel word's meaning by asking them to rate the plausibility of novel sentences containing the previously learned pseudowords ("They used the MARF/GLUE" vs. "She drove the MARF/GLUE"). Participants were able to extrapolate the meaning of the novel words and showed facilitated semantic access as well as higher plausibility ratings. These findings indicated that after a single exposure in strongly constraining contexts, adults were able to extrapolate novel word meanings from one context to another.

In a follow-up experiment, Borovsky, Elman, and Fernald (2012) used the same learning contexts of strongly and weakly constraining sentences, but focused more directly on how novel words altered the implicit structure of participants' lexicons after a single exposure. After the initial learning phase (identical to the first experiment), they presented the young adult participants with a priming phase. The novel words were used as primes, whereas existing words with the same, related, or unrelated to the expected (but never presented) meaning were presented as targets (to use a similar example: MARF—glue; MARF—scissors; MARF—road). Following constraining contexts, the novel words primed synonymous and related meanings as strongly as their expected counterparts. Based on these findings, Borovsky, Elman, and Kutas (2012) concluded that adult readers use predictions generated by constraining contexts after a single learning opportunity to update their lexicons and integrate novel word meanings to existing semantic structures.

As a comprehension strategy, prediction may be as useful for children as it is for adults, but it may not be helpful as a learning mechanism. Infants and toddlers need diverse (Borovsky et al., 2016) or repeated contexts (Axelsson & Horst, 2014; Horst et al., 2011) to extrapolate and retain novel word meanings. Toddlers and preschoolers have also been shown to need multiple learning opportunities to generate most effective predictions (Bion et al., 2013; Gambi et al., 2018; Mani et al., 2016), while early adolescents reinforce novel word learning by using successful predictions following three exposures (Abel et al., 2018). Moreover, toddlers and preschoolers extrapolate novel meanings based on prediction errors (Gambi et al., 2021; Reuter et al., 2019). Recent meta-analyses of predictive processing data indicate that even if children use prediction as a comprehension mechanism, it may still not be a reliable way to expand one's vocabulary. Rather, efficient prediction may be a consequence of the speakers' increasing vocabulary knowledge and experience with diverse language contexts (Huettig & Mani, 2016; Rabagliati et al., 2016).

Neuropsychological word learning theories based on adult data indicate that while multiple exposures in different contexts and presentation types across days are necessary for complete consolidation in the lexicon (with the help of the hippocampus), there is evidence that neocortical mechanisms facilitate the immediate learning of certain word form features after a single exposure (Davis & Gaskell, 2009; Shtyrov et al., 2010; Taylor et al., 2013). This leads to a distinction between lexical configuration and lexical engagement, with the first representing immediate word form learning and the second representing the full lexical entry of that word form and all its dependencies in the lexicon (Bakker et al., 2015; Coutanche & Thompson-Schill, 2014; Leach & Samuel, 2007). With relation to using predictive contexts for novel word learning, we can hypothesize that the immediate lexical configuration of novel word forms is facilitated by predictive processing in supportive contexts, but full lexical engagement in the lexicon requires larger vocabulary knowledge and extended experience with a novel word form (in line with Huettig & Mani, 2016; Rabagliati et al., 2016).

Nevertheless, direct manipulations of contextual constraint for novel word acquisition such as the one-shot learning paradigm of Borovsky et al. (2010; 2012) show that predictive processing facilitates novel word learning, but have so far only been tested with university educated young adult speakers with expert language skills. The question remains whether school-aged children who can already formulate predictions and have some intermediate experience with language apply these prediction mechanisms in novel word learning. Thus, the present study aims to apply the one-shot learning paradigm to investigate the abilities of 7- to 13-year-olds to use contextual constraint to disambiguate upcoming novel words' meanings and to integrate the novel words in their existing vocabulary.

One reliable way to assess readers' reliance on previous contexts to formulate expectations about upcoming meanings has been the N400 event-related potential (ERP) effect (Brouwer et al., 2017; Kutas & Federmeier, 2011; Swaab et al., 2012). Larger N400 amplitudes reflect difficulties in the lexico-semantic processing of unexpected or unpredictable inputs for adults (Boudewyn et al., 2015) as well as children (Friedrich & Friederici, 2006). Most likely generated by left temporal cortical networks (Lau et al., 2008, 2016), the N400 response appears to reflect the processing result of several cerebral feedforward and feedback networks, ultimately leading to the successful construction of conceptual meaning representations (Federmeier, 2007). The N400 amplitudes have a strong negative correlation with a word's cloze probability, or the percentage of people who supply a particular continuation based on the previous context (Wlotko & Federmeier, 2012). With regard to language learning, the N400 has reliably been used to investigate the development of semantic memory and lexicon growth as a consequence of the learners' expanding vocabularies in their native language (Friedrich & Friederici, 2006), as well as an index of successful learning and integration of never before encountered novel words and meanings (Borovsky et al., 2010; Borovsky, Elman, & Kutas, 2012; Davenport & Coulson, 2011).

Unlike adult studies, which focus on word prediction during sentence comprehension (as well as semantic priming), N400 investigations of language processing during early childhood have mostly been restricted to semantic priming paradigms or word-picture matching tasks (Junge et al., 2021). Semantic priming refers to the facilitation of target processing (for example, of the word *pear*) following the presentation of semantically related prime words (such as *apple*). In novel word learning, semantic priming effects can be used as an index of lexical consolidation and engagement in the lexicon. If a novel word (such as *fielp*) is integrated in the learner's semantic network as a synonym of *apple*, then it follows that it should facilitate a) the processing of the target word *apple*, as well as b) the processing of semantically related words such as *pear* (Sirri & Rämä, 2015; Tamminen & Gaskell, 2013). Previous semantic priming N400 findings show successful lexico-semantic facilitation for related picture-word or word-word pairs as early as 18–19 months of age (Friedrich & Friederici, 2004; Rämä et al., 2013; von Koss Torkildsen et al., 2006; von Koss Torkildsen et al., 2007). A few preadolescent findings indicate that N400 amplitudes to incongruent semantic priming pairs become indistinguishable from those of adults around 7 years of age (Cummings et al., 2008), although this effect is less nuanced when these words are integrated in full sentential contexts (Atchley et al., 2006; Benau et al., 2011; Holcomb et al., 1992). Therefore, by about 7 years of age, children show adult-like facilitation of word processing in supporting contexts as reflected by the N400. What is unclear from the previous literature is whether this translates to an ability to use predictive contexts to guess and learn completely novel word meanings especially after a single exposure. Using the terminology of Leach and Samuel (2007), by the age of 7, children appear to be able to achieve lexical configuration of novel words using their immediate contextual support. What we set out to investigate in the present study is whether children are further able to benefit from that single exposure to initiate lexical engagement of the novel word meanings in their lexicons.

In sum, in the present study, we examined whether primary and middle-school-aged children use prediction when mapping meaning to novel word forms in a way similar to that previously reported for young adults (Borovsky, Elman, & Kutas, 2012). To that end, we applied the same one-shot learning paradigm (Borovsky, Elman, & Kutas, 2012) and adapted it to auditory presentation a) to increase the similarity to the children's real-world language experience and b) to control for print exposure and reading ability in the younger population. In line with the original study, we used ERP methodology and assessed age differences in language processing in two phases. In the learning phase, we manipulated sentential constraint (strong vs. weak) and compared the N400 amplitudes for expected words and novel pseudowords to examine whether children took advantage of constraining contexts to formulate expectations for the meaning of upcoming inputs (see Table 1 for example sentences and word/pseudoword completions). We also investigated the effect age had on children's ability to use contextual constraint to formulate predictions of upcoming inputs.

In the following semantic priming phase, we presented the same words and pseudowords as primes and measured our participants' N400 responses to the following semantically unrelated, semantically related, identical (to the word prime), or synonymous (to the pseudoword prime) target words. This way we could investigate whether children could map the meanings they inferred in strongly constraining contexts to the novel pseudowords and to what extent they could integrate them in their lexicons. We expected reduced N400 amplitudes to target words primed by pseudowords that had previously appeared in strongly constraining sentences compared to pseudowords learned in weakly constraining sentences, indicating that participants had successfully mapped the predicted meanings to the novel pseudoword forms during the learning phase and had begun to build semantic associations with similar exemplars in their lexicon.

2 | METHOD

2.1 | Participants

Thirty-four children participated in our experiment. Participants' parents were approached during children's university lectures and in parent groups online, as well as from the participant database of the Lifespan Cognition Laboratory in Saarland University. Each participant's parents as well as the participants themselves were informed of the nature and length of the experiment and their ability to revoke their consent to participate at any point. Parents signed informed consent forms indicating their desire for their children to participate in the study. Children received €25 for participating in the 2.5 hr, one-session experiment.

Data from 9 participants were excluded due to excessive number of EEG artifacts (>30% of all epochs), leaving 25 participants for the final analysis, with ages ranging from 7;1 to 13;4 years (*mean age* = 9;10). All participants were native speakers of German and had normal or

TABLE 1 Examples of sentences and prime pairs in each condition

(a) Learning phase context sentences (known word/pseudoword)			
Strong constraint	Als die Hexe Schneewittchen im Wald traf, gab sie ihr einen *Apfel/Fielp*		
	When the Witch met Snow White in the forest, she gave her an apple/fielp		
Weak constraint	Weil das Mädchen Hunger hatte, aß es einen *Apfel/Fielp*		
	Because the girl was hungry, she ate an apple/fielp		
(b) Priming phase pairs (prime-TARGET)			
	Identical	**Related**	**Unrelated**
Known word	Apfel-APFEL	Apfel-BIRNE	Apfel-SOCKE
	apple-APPLE	*apple-PEAR*	*apple-SOCK*
Pseudoword	Fielp-APFEL	Fielp-BIRNE	Fielp-SOCKE
	fielp-APPLE	*fielp-PEAR*	*fielp-SOCK*

Note: We created the stimuli following the one-shot learning setup of Borovsky, Elman, and Fernald (2012). All stimuli (learning and priming phase) were presented as audio, read by a native speaker of German at a child-friendly rate. For the learning phase, we used context sentences of high or low constraint (based on cloze probability ratings gathered with a separate participant group of the same age) with a known word or pseudoword ending. Pseudowords were created by a native speaker to be pronounceable in German and appear to be of the same gender and word type as the original, while being orthographically distinct. Unlike Borovsky, Elman, and Fernald (2012), in our stimuli the word/pseudoword endings acted as their own controls, appearing in both strong or weak constraint sentences across different presentation lists. For the priming phase, the same known words and pseudowords were used as primes to targets of identical, related, and unrelated meanings.

corrected-to-normal vision and no hearing problems according to self-reports.

2.2 | Materials

Borovsky, Elman, and Kutas (2012) assigned sentences with cloze probability of 0.17–0.78 to a weak constraint condition and sentences with cloze probability above 0.78 to a strong constraint condition. Here, in order to achieve a clear contrast between the experimental conditions, as children might be less sensitive to finer cloze probability gradings, we set an ad hoc level of <0.30 to weak constraint and >0.70 to strong constraint conditions.

In order to assign sentences to the strong and weak constraining conditions, we performed two cloze probability pretests. For the first pretest, a native speaker expert created 142 potentially strongly and weakly constraining context sentence pairs. We split the pairs in two lists and presented the pen-and-paper pretest to university students (n = 41, age range = 18–25 years), who received €5 for their participation. Of the resulting completed sentences, 81 pairs matched our ad hoc criteria of <0.30 for weak constraint and >0.70 for strong constraint conditions.

In the second pretest, the resulting strong and weak constraint contexts, without completions, were presented to 44 first- and second-grade native speakers (age range = 6–9 years). Each child listened to the contexts as read by a native speaker of German and verbally provided what they judged to be the best completion. Of the original 81 pairs, 52 pairs were left that matched our ad hoc criteria. None of the children who provided norms for the pretest participated in the current study. Detailed description of the methods and results of the two pretests, as well as the original German audio files and descriptive statistics of the final stimulus set, are presented in detail in our online supplementary folder (https://osf.io/2cfjd/). The materials are available for reuse under a CC-BY4.0 license.

2.2.1 | Learning phase materials

To complete the design, we created 52 pseudowords (novel words) to match the 52 word completions provided in the pretests (see Table 1a for example sentences from the learning phase). The pseudowords matched the word completions by length, number of syllables, and perceived grammatical gender (as judged by a native speaker of German).

We presented all stimuli auditorily to avoid reading ability differences in our sample. All stimuli were read by a native German speaker at a natural rate for the age group. To avoid baseline issues based on co-articulations of the context and the following word or pseudoword continuation, we recorded and presented the word and pseudoword targets separately from the preceding contexts. The audio contexts (up to the sentence-final target) took between 3820 and 9369 ms. The targets' length varied between 406 and 1350 ms (see the online supplementary materials at https://osf.io/2cfjd/ for all audio materials).

2.2.2 | Priming phase materials

In order to measure whether children used the previous sentence context to map the expected meanings to the novel pseudowords, we applied an implicit priming task. For each word continuation and its corresponding pseudoword synonym from the learning phase, we presented the identical target, a semantically related, and a semantically unrelated target (see Table 1b). The known word primes and targets were matched as closely as possible on word frequency, word length, syllable number, concreteness, familiarity, and imageability. They did not belong to the same orthographic neighborhood and were judged not to be highly associated (such as mouse—CHEESE) by a native speaker expert. Pseudowords were used as synonymous primes as their word counterparts for each constraint condition: for example, Fielp was assumed to be a synonym of apple (Apfel), a related prime for pear (BIRNE), and an unrelated prime for sock (SOCKE). The length of the audios for primes ranged between 406 and 1350 ms, while the target word audios ranged between 133 and 1265 ms (see the online supplementary materials at https://osf.io/2cfjd/ for all audio materials).

2.3 | Procedure

Participants were seated in a sound-attenuated, electrically-shielded room. Stimuli were presented auditorily via speakers, using E-prime 3.0 (Psychology Software Tools, 2016). Each experimental session consisted of four blocks of learning, followed by priming phases, interspersed with three 5–10 min breaks (see Figure 1 for a visual schematic).

To control for language skills development, we applied four standardized measures: semantic and phonemic verbal fluency word counts (Troyer et al., 1997), Peabody Picture Vocabulary Test (Lenhard et al., 2015), and a Color Symbol Substitution Test (a children's version of the Digit Symbol Substitution Test).

2.3.1 | Learning phase procedure

For the learning phases, we created 4 counterbalanced lists of the 52 pairs of sentences, such that each participant heard both strongly and weakly constraining sentences, but with either the word or pseudoword ending. Each learning list was split in 4 learning blocks of 13 sentences each (see Figure 1). Overall, all participants heard all conditions.

In order to ensure the participants' attention during the auditory presentation of the sentences, a simple secondary visual task was presented during the learning phase only. We presented a drawing of a flower before and after each sentence, requiring participants to press a button corresponding to whether the flower drawings seen before and after each sentence were identical or not.

Participants were told a backstory about a woman, "Paula," who has recorded some sentences and drawn some flowers for them. They were asked to try to follow whether the flowers shown before and after each sentence matched and given an example. No specific mention was made about the content of the sentences. The children were not asked to memorize the sentences or the critical items.

2.3.2 | Priming phase procedure

We presented a priming block after each of the four learning blocks. For each priming block, the participants heard the word/pseudoword endings of the preceding learning block followed by all three target conditions (identical, related, and unrelated target) in randomized order. This resulted in 156 prime-target pairs for each list (39 per priming block).

The length of the audios for primes ranged between 406 and 1350 ms, followed by a pause of 200 ms and the target word audios ranging between 133 and 1265 ms. The participants were told that the reader Paula could not remember all of the previous sentences, apart from a few words, which she would read aloud again. They had no additional task during the priming blocks, but were encouraged to sit as still as possible and to try to see if they could recognize the words they had already heard during the previous learning block. Screenshots of the instructions and their translations from German can be found in our online supplementary folder (https://osf.io/2cfjd/).

Each testing session lasted about 2.5 hours, including demographic questionnaires, breaks, and EEG setup and clean-up time. During the breaks and setup time, participants read, colored, watched cartoons, or played board games with the experimenters.

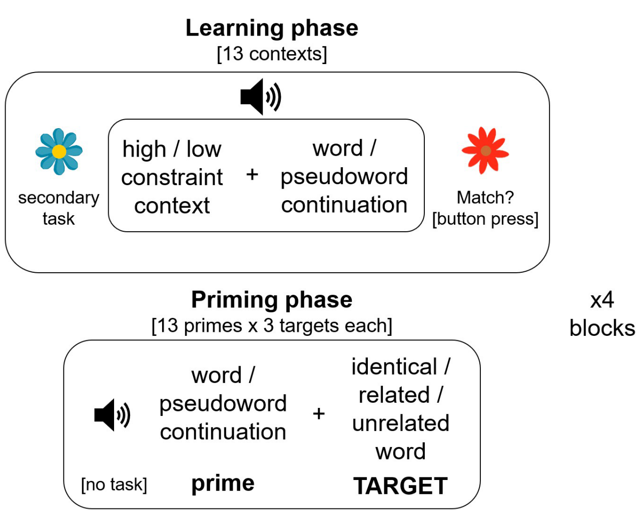

FIGURE 1 Sample block of the learning and priming phases presented to children. Each block consisted of 1) a learning phase with 13 auditory contexts and a visual match/mismatch secondary task followed by 2) a priming phase with 39 randomized auditory prime-target pairs with the preceding learning phase continuations as primes to 3 different target words (identical, related, and unrelated). The experiment consisted of four blocks. Figure by Vergilova et al. (2021); available at https://osf.io/wx3gs/ under a CC-BY4.0 license

2.4 | EEG recording

Data were recorded at 39 scalp sites according to the 10–20 system (Homan et al., 1987) using active Ag/AgCl electrodes, embedded in a 64-channel elastic cap (actiCAP Snap, Brain Products GmbH). Impedances were kept below 20 kΩ. Horizontal eye movements were monitored by placing electrodes at the outer canthi of each eye. Vertical eye movements were monitored by placing electrodes above and below the left eye. EEG was recorded continuously at a 500 Hz rate with no online filters. Data were then bandpass filtered offline from 0.01 to 30 Hz (slope 24 dB) and re-referenced to the mean of the left and right mastoids. Data preprocessing was performed using MATLAB, specifically with the EEGLAB toolbox and ERPlab plugin (Lopez-Calderon & Luck, 2014). We applied independent component analysis (ICA) in order to correct for vertical and horizontal eye movements, as participants were not instructed to control for those. Additionally, epochs with amplitudes larger than ±100 Hz were automatically rejected, as were epochs where one or more channels registered slow sustained activity of ±100 Hz for longer than 200 ms. This resulted in a loss of ~15% of epochs per participant (range: 1.4%–29.6%), summarized in Table 2 per age group.

ERPs were timelocked to the onset of the sentence final target (learning phase) and second stimulus in the prime-target pair (priming phase). ERPs were averaged

TABLE 2 Age-group distribution

Age (years)	7	8	9	10	11	12	13
Number of participants	1	6	4	2	6	5	1
Secondary task accuracy	83%	83%	94%	72%	89%	96%	62%
Percent rejected epochs	19.7%	23.9%	19.3%	14.6%	12.7%	8%	1.9%
PPVT raw score	159	163	161	184	187	190	202
Phonemic verbal fluency	6	6.4	6	5.5	10	8.8	NA
Semantic verbal fluency	11	18.4	18	17	20	22.4	NA

Note: Descriptive statistics per age group: Mean (SD). In the current study, age was analyzed as a continuous variable ranging from 8 to 12 years, with the single 7- and 13-year-old participants recoded as 8- and 12-year-old, respectively (see Learning and Priming phase analysis sections). Accuracy to secondary visual task was reported as the mean of hits and correct rejections. Participants with more than 30% loss of epochs overall were excluded from the analysis (see EEG analysis section). The raw PPVT score reflects participants' passive vocabulary skills with maximal potential score of 228. Semantic and phonemic verbal fluency reflects the number of correct words produced in 1 minute (following a prompt to produce words for animals and words starting with "S," respectively).

across each sentential ending per condition in the learning phase and each target word in the priming phase. In the priming phase, we specifically focused on ERPs elicited by the target words and not the prime words or pseudowords, which allowed us to avoid the repetition effects resulting from the participants having already heard the same primes three times per block. The continuous artifact-free EEG was divided into epochs from 200 ms before to 1200 ms after target word onset, and epochs were baseline-corrected relative to the 200 ms pre-stimulus window. Auditory N400 amplitudes were grand averaged at 300–500 ms after the onset of the target for the learning and priming phases. The time-windows were based on visual inspection and following previous findings on auditory N400 effects in these age groups for sentence processing (Holcomb et al., 1992; Juottonen et al., 1996) and single word semantic priming (Byrne et al., 1999; Henderson et al., 2011).

3 | RESULTS

3.1 | Behavioral results

3.1.1 | Standardized test measures

Results indicated that with increasing age semantic ($r = 0.41$, $p < .05$) and phonemic ($r = 0.49$, $p < .05$), verbal fluency word count scores increased, as well as passive vocabulary size as reflected by the PPVT raw scores ($r = 0.65$, $p < .001$). Language-independent processing speed decreased with increasing age (Color Symbol Task Hits: $r = -0.73$, $p < .001$; Color Symbol Task Correct Rejections: $r = -0.67$, $p < .001$), while accuracy on the Color Symbol Task increased ($r = 0.41$, $p < .05$). Mean accuracy and individual difference scores per age group are summarized in Table 2. For a full correlation matrix of the secondary behavioral measures, see our online supplementary materials at https://osf.io/2cfjd/.

3.1.2 | Learning phase: Secondary task performance

Performance on the secondary task was above chance and near ceiling on average ($M = 88\%$; $range = 62–100\%$), confirming that participants were attending to the task during the learning phase. In the analyses of the secondary task performance, age was not a significant predictor of accuracy: $Adj.\ R^2 = -.05$, $\beta = 0.00$, $SE = 0.01$, $t = 0.17$, $p = .87$, but explained 40% of the variance in reaction times to correct responses (hits and correct rejections): $Adj.\ R^2 = -.40$, $\beta = -12.34$, $SE = 3.21$, $t = -3.84$, $p < .001$. With increasing age, children became faster at their secondary task responses. However, there were no age differences in response accuracy.

3.2 | ERP results

ERP data were organized and prepared in R (Version 3.6.1) and analyzed in Julia (Version 1.2.0) by fitting Linear Mixed-Effects Models using the Mixed Models package (Version 2.1.2). β-Estimate, standard error, z-value, and p-values are reported as well as confidence intervals for significant effects only ($p < .05$; $|z| > 2.0$). Confidence intervals were extracted utilizing parametric bootstrapping.

The design of our current experiment and the number of participants, items, and electrode sites was best suited for a parsimonious linear mixed model approach (based on recommendations listed in Bell et al., 2019; Heisig et al., 2017; Heisig & Schaeffer, 2019; Matuschek et al., 2017) We followed the parsimonious mixed models approach as described by Bates et al. (2015)), where factors or interactions between factors were dropped from the random structure according to the variance in the data they accounted for. These contributions were extracted utilizing a principal component analysis (PCA) of the random-effects variance–covariance estimates from the mixed-effects model. Following the proposed approach to arrive at a parsimonious model, we computed the zero-correlation random structure model in a first step. In the following steps, correlations were reintroduced to the random structure in a series of steps to minimize model over-specification and to arrive at the most parsimonious fixed and random effect structure. In the following sections, we report results stemming from the final models yielding the lowest AIC value (see our online supplementary materials at https://osf.io/4j9aq/ for full model outputs).

3.2.1 | Learning phase analysis

For the ERP analysis of the learning phase, age, word status (word vs. pseudoword), and constraint (strong vs. weak constraint) were included as fixed factors. Age was included as a continuous variable, scaled to the range from −.5 to .5 in order to resemble the contrast coding of the other factors[1]. The contrasts for both word status and constraint were effect-coded (−.5 for pseudowords and strong constraint, and .5 for words and weak constraint, respectively). Additionally, anteriority was included as a fixed factor in order to attest for scalp distribution of the ERP effect. Anteriority as a factor was averaged across electrodes in three regions of interest (ROIs) for frontal (F5, F3, F1, Fz, F2, F4, F6, FC5, FC3, FC1, FC2, FC4, FC6), central (C5, C3, C1, Cz, C2, C4, C6, CP5, CP3, CP1, CP2, CP4, CP6), and posterior (P7, P5, P1, Pz, P2, P6, P8, PO3, POz, PO4, O1, Oz, O2) electrode sites. The three anteriority contrasts were then coded by way of two comparisons. Firstly, we contrasted the frontal against central and parietal ROIs and, secondly, central against parietal ROIs.

3.2.2 | Priming phase analysis

The analysis of the priming phase followed the same approach as the learning phase and contained the same fixed effects with an identical structure: age (continuous), word status (word vs. pseudoword), constraint (strong vs. weak constraint), and anteriority (frontal, central, posterior). In addition, relatedness of the target word to the prime word/pseudoword was included as a three-level factor (unrelated, related, and identical/synonymous target). The comparisons for this factor were coded such that a first comparison (R1) encoded the difference between unrelated targets and the mean of related and identical targets, while a second comparison (R2) encoded the difference between related and identical targets.

3.2.3 | Learning phase N400 results (300-500 ms)

There was a main effect of Ant1 (frontal vs. central and posterior ROIs): $\beta = -1.98$, $SE = 0.53$, $z = -3.72$, $p < .001$, CI = [−3.08; −1.00] as well as Ant2 (central vs. posterior ROIs): $\beta = -1.36$, $SE = 0.38$, $z = -3.57$, $p < .001$, CI = [−2.12; −0.62]. The effects were qualified by two two-way interactions of Ant1 and word status ($\beta = 2.57$, $SE = 0.70$, $z = 3.66$, $p < .001$, CI = [1.08; 3.81]) and Ant2 and word status ($\beta = 1.99$, $SE = 0.67$, $z = 2.97$, $p < .01$, CI = [0.63; 3.24]): pseudowords elicited more negative amplitudes compared to words over central and posterior electrode ROIs versus frontal ones, as well as more negative amplitudes for posterior than central ROIs (see Figure 2). The topography, timing, and polarity of the effect implied that pseudowords elicited an N400 effect compared to known words.

Additionally, the three-way interaction of age, word status, and constraint was significant: $\beta = -5.96$, $SE = 2.96$, $z = -2.02$, $p < .05$, CI = [−10.94; 0.20]. The negativity for pseudowords as compared to words was largest in strongly constraining sentences for younger children and diminished with increasing age (see Figure 3 for EPRs averaged over the Pz site).

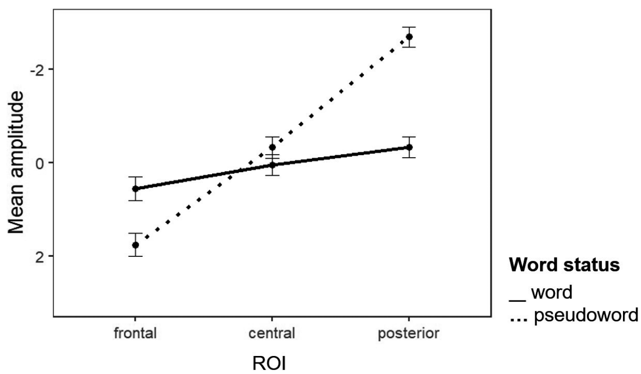

FIGURE 2 Learning phase word status effect over frontal, central, and posterior ROIs. Word status effect over anteriority condition. Negativity is plotted upwards. Error bars represent standard error per condition. Figure by Vergilova et al. (2021); available at https://osf.io/v2cqa/ under a CC-BY4.0 license

[1]Due to recruitment difficulties with regard to COVID-19, the distribution of participants in each age group was uneven, with only one 7-year-old and one 13-year-old participant. Out of concerns that this would affect the linear fit of age as a continuous variable, the 7-year-old participant was treated as a part of the 8-year-old group and the 13-year-old participant was treated as a part of the 12-year-old group.

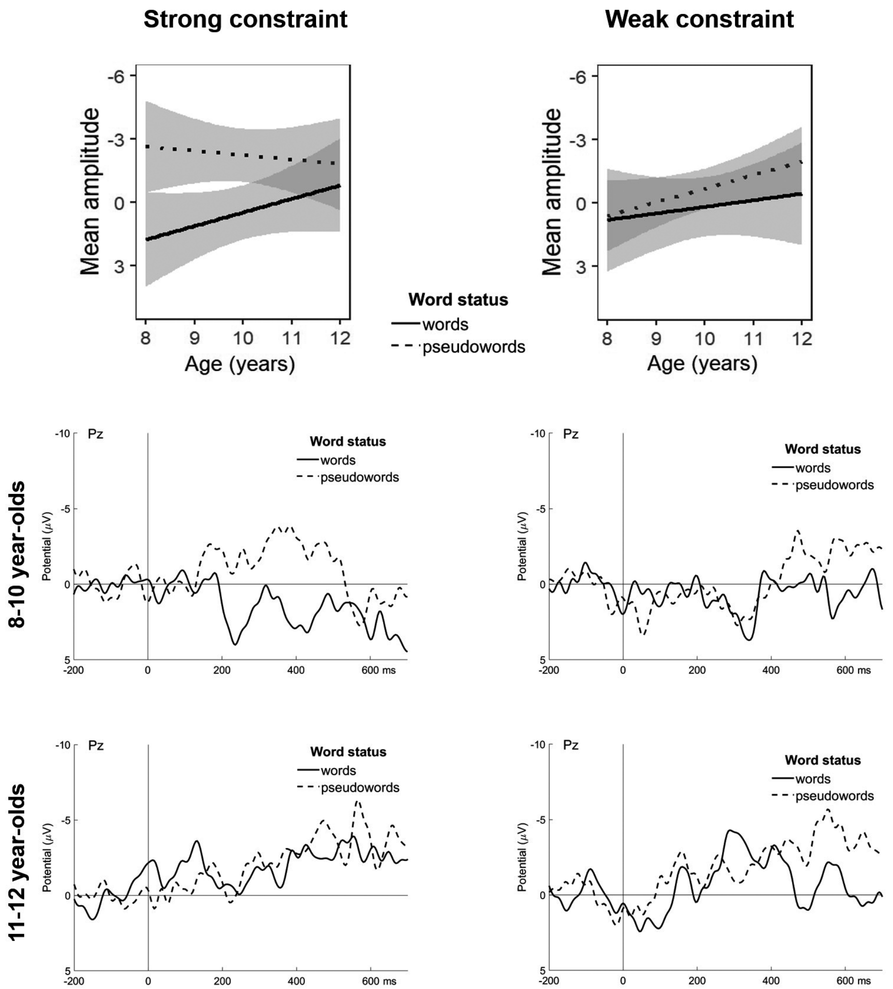

FIGURE 3 Learning phase word status effects for strong and weak constraint conditions. Line charts and ERP plots of age by constraint by word status interaction. Shading represents the assumed variance of the linear fit of age as a continuous variable. ERP plots averaged for illustrative purposes over younger (8–10) and older (11–12) participants (Pz site) timelocked to onset of word and pseudoword completions. Negativity is plotted upwards. Figure by Vergilova et al. (2021); available at https://osf.io/8qmk3/ under a CC-BY4.0 license

In sum, during the learning phase, children exhibited a sensitivity to sentential constraint and to word/pseudoword status. For younger participants in particular, the N400 effect for pseudowords compared to words was greatest following strongly compared to weakly constraining sentences (Figure 4).

3.2.4 | Priming phase N400 results (300-500 ms)

Both anteriority comparisons were significant for the N400 time window. Ant1 (frontal vs. central + posterior ROIs): $\beta = -1.47$, $SE = 0.33$, $z = -3.35$, $p < .01$, CI = [−2.51; −0.45] and Ant2 (central vs. posterior ROI): $\beta = -1.50$, $SE = 0.54$, $z = -2.71$, $p < .001$, CI = [−2.35; −0.75]. The effect of Ant1 was qualified by two-way interactions of constraint and Ant1 ($\beta = -1.17$, $SE = 0.46$, $z = -2.55$, $p < .05$, CI = [−2.16; −0.41]) and R1 (unrelated vs. related + identical) and Ant1 ($\beta = 1.58$, $SE = 0.45$, $z = 3.50$, $p < .001$, CI = [0.75; 2.49]).

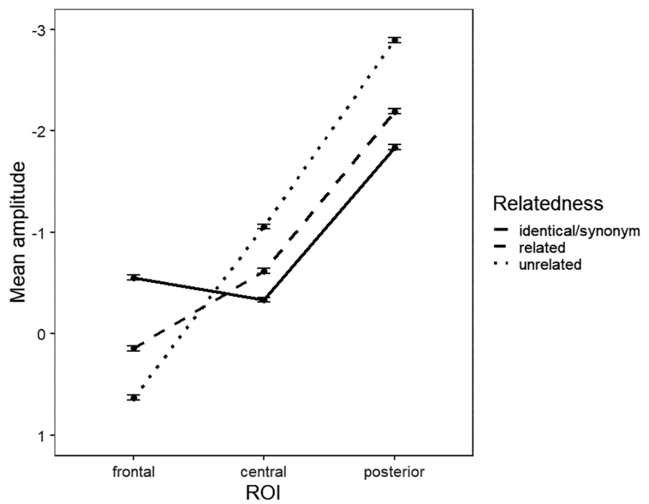

FIGURE 4 Topography of the relatedness effect. Mean amplitudes to identical/synonymous, related, and unrelated target words over each ROI. Negative is plotted upwards. Error bars represent standard error per condition. Figure by Vergilova et al. (2021); available at https://osf.io/5w4gr/ under a CC-BY4.0 license

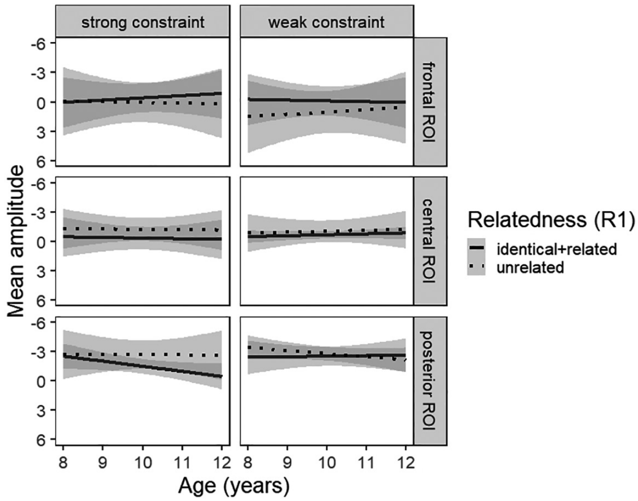

FIGURE 5 Priming phase relatedness effect over age and constraint. Prime-target relatedness effect for primes previously learned in strong and weak constraint conditions across age. Negative is plotted upwards. Shading represents the assumed variance of the linear fit of Age as a continuous variable. Figure by Vergilova et al. (2021); available at https://osf.io/xp6yn/ under a CC-BY4.0 license

The two-way interactions were further qualified by three four-way interactions: age, constraint, R1, and Ant1 ($\beta = -5.39$, $SE = 2.66$, $z = -2.02$, $p < .05$, CI = [−10.53; 0.05]), age, constraint, R1, and Ant2 ($\beta = -4.52$, $SE = 2.03$, $z = -2.23$, $p < .05$, CI = [−8.79; −0.99]), and word status, constraint, R1, and Ant2 ($\beta = -2.81$, $SE = 1.32$, $z = -2.13$, $p < .05$, CI = [−5.34; −0.26]) (Figure 5).

In sum, during the priming phase, we found that when initially learned in strongly constraining contexts, pseudoword as well as word primes elicited larger N400 modulations to unrelated target words as compared to related and identical target words. This N400 effect of relatedness was largest over posterior electrode sites and increased with age (Figure 6).

4 | DISCUSSION

The goal of the present study was to investigate age-related differences in how children (7–13 years) use predictions generated by a single exposure in strongly or weakly constraining context to map predicted meanings to novel word forms (one-shot learning). We further examined to what extent these novel word forms were integrated into the children's semantic networks. We assessed German native speaking children in a one-session EEG study consisting of four learning and four priming phase blocks. In the learning phases, children were presented with audio recordings of high and low constraining sentence contexts followed by either plausible words or naturally-sounding pseudowords, while attending to a secondary visual picture-matching task. In the subsequent priming phases, children passively listened to prime-target pairs, which consisted of the previously learned word and pseudoword completions as primes and the same, semantically related or semantically unrelated target words. Using implicit semantic priming allowed us to differentiate between (a) the effects of immediate lexical consolidation between the novel word forms and the expected meanings, as constrained by the sentential context the words were learned in, and (b) the effects of subsequent deeper lexical engagement of the novel word forms with other vocabulary entries of related meaning.

With the current experiment, we build on previous findings in the literature discussing whether children use predictive contexts to generate hypotheses about novel words' meanings and integrate those novel words into their vocabulary, or whether an adult-level vocabulary is a prerequisite for this type of word learning (Huettig & Mani, 2016; Rabagliati et al., 2016). Previous research focuses mainly on the lack of evidence that toddlers and preschool-aged children reliably benefit from predictive contexts when learning novel words (Borovsky, Elman, & Fernald, 2012; Mani & Huettig, 2012). To our knowledge, the only evidence of reliable mapping between predicted meanings and novel word forms and comes from young adult data (Borovsky et al., 2010; Borovsky, Elman, & Kutas, 2012). Therefore, in order to investigate a larger spectrum of predictive learning development, we focused on pre- and early adolescents (7–13 years).

Our study revealed two crucial new findings: (a) younger children relied heavily on supporting sentential contexts to access incoming novel inputs, but experienced difficulties consolidating these inputs in their lexicon based on only one exposure; (b) older children used strongly constraining contexts to create expectations of novel word meanings and were able to integrate these novel word forms into their lexicon after a single exposure. We unpack these findings separately for the learning and priming phases in the following sections.

4.1 | Learning phase: Children's novel word acquisition in context

During the learning phase, unexpected novel pseudoword completions elicited reliably more negative amplitudes compared to expected words over centro-posterior ROIs. Crucially, this pseudoword N400 effect was modulated by the sentential constraint in which the completions were presented and the age of the listeners. Younger children showed greater N400 modulations for novel pseudoword compared to word completions presented in strongly

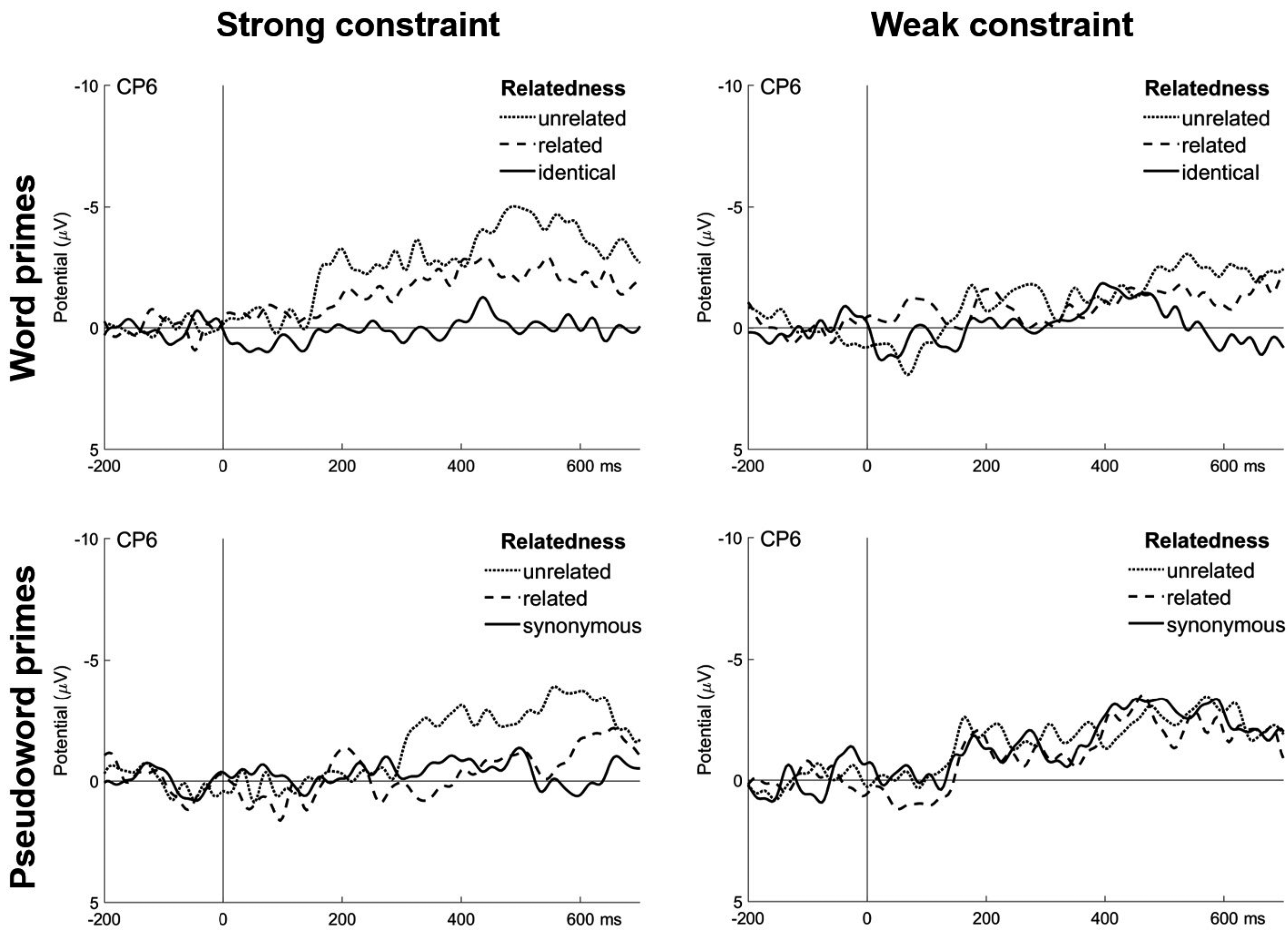

FIGURE 6 Priming phase ERPs. Priming phase. Grand averaged ERP plots of unrelated, related, and identical/synonymous targets (CP6 site) timelocked to onset of target word preceded by word or pseudoword primes presented in strong or weak constraint sentences during the earlier learning phase. Negative is plotted upwards. Figure by Vergilova et al. (2021); available at https://osf.io/2zw79/ under a CC-BY4.0 license

constraining contexts. We found no reliable differences in N400 amplitudes between novel pseudoword and word completions when the sentential constraint was weak and no expectations for upcoming input could be built. The effect of constraint on the N400 amplitudes to word and pseudoword completions diminished with increasing age. We interpreted this interaction as an indication that, compared to early adolescents, younger preadolescents relied on supporting contexts to narrow down the potential upcoming continuations and therefore exhibited greater difficulties (larger N400 modulations) when the presented novel pseudowords mismatched these expectations.

Unlike previous theories that predictive processing may require access to larger vocabularies and richer linguistic experience (Rabagliati et al., 2016), our data show an inverse relationship between age (as a proxy of linguistic experience) and constraint-based expectations. Younger participants relied heavily on strong contextual constraint to create expectations for upcoming inputs. When constraint was weak, younger children accessed word and novel pseudoword continuations with equal difficulty. Alternately, for older children, the semantic access of upcoming continuations was not affected by how constraining the previous context was, only how expected the upcoming continuations were (e.g., existing words vs. novel pseudowords). As such, our older children's results are in line with previous child and adult findings that show N400 modulations vary independently of contextual constraint (Abel et al., 2018; Borovsky et al., 2010; Borovsky, Elman, & Kutas, 2012; DeLong et al., 2011; Federmeier et al., 2007). Our findings suggest that there is an effect of contextual constraint over semantic access as indexed by the N400, but it diminishes with age. The greater sensitivity of younger children to contextual constraint could be taken as evidence that they benefit from a narrowed down pool of potential continuations as they access upcoming input. This goes in line with eye-tracking findings that suggest toddlers with lower active vocabulary have more difficulties fixating targets embedded in weak versus strong constraint sentences (Mani & Huettig, 2012).

In all, the findings from the learning phase suggest that children between 7 and 13 years of age show adult-like surprisal effects when encountering novel pseudowords in context. Additionally, we find that the effect of sentential constraint on the ability of comprehenders to detect unexpected input was significant up to about 10 years and diminished with age.

4.2 | Priming phase: Novel word consolidation in children's vocabularies

During the priming phase of our study, we looked into the N400 amplitudes timelocked to the auditory presentation of identical/synonymous, related, and unrelated target words primed by the words and pseudowords previously learned in strongly or weakly constraining sentences. In line with our initial hypotheses and the findings of Borovsky, Elman, and Kutas (2012), we found that unrelated targets elicited significantly larger N400 modulations than identical and related target words: (a) when the primes were initially presented in strongly constraining sentences, (b) regardless of whether the primes were words or novel pseudowords. Regardless of our participants' ages, after a single learning opportunity in strongly constraining sentences, novel pseudoword primes (e.g., *fielp*) facilitated the comprehension of synonymous (e.g., *apple*) and related (e.g., *pear*) target words just as successfully as existing words of the identical meaning (e.g., *apple*). Conversely, when the pseudoword primes were not presented in supporting contexts during the initial learning phase, they were not mapped to the expected meanings and elicited no reliable semantic facilitation N400 effects. Our findings indicate that on average our participants used the meaning expectations they built based on contextual support to integrate novel words in their lexicon after a single exposure. The children seemed to have constructed a rough meaning representation of the newly learned form, in line with young adult data (Borovsky, Elman, & Kutas, 2012).

However, taking age into account, learning from prediction did not come easy to all participants. The participants' age modulated their N400 responses to prime-target relatedness. When the word and pseudoword primes were initially presented in strongly constraining sentences during the learning phase, the semantic priming N400 attenuations for related and identical versus unrelated prime-target pairs in the subsequent priming phase increased with age. It appeared that, even though our youngest participants were more sensitive to constraint during the learning phase, it was the older participants that showed stronger priming associations between the novel words and the expected meanings. Together, the learning and priming phase N400 modulations for our older participants (starting at about 10 years of age) showed a pattern closer to young adult data (Borovsky, Elman, & Kutas, 2012), with a reduced sensitivity to constraint during the initial learning phase and a semantic association between expected meanings and novel word forms during the second priming phase.

Despite the fact that the younger children in our experiment relied on the immediate sentential constraint for effective semantic access of upcoming information during the initial learning task, they did not show later priming associations between novel words and their expected meanings. This interpretation aligns with prior work that suggests novel word learning for younger children may be associated with more immediate, potentially attention-driven, disambiguation between expected and presented inputs, rather than a sustained learning strategy (Kucker et al., 2018; Samuelson et al., 2017). Moreover, since neuroimaging investigations of adult word learning indicate that lexical consolidation requires the involvement of neocortical structures such as the anterior superior temporal cortex (Davis & Gaskell, 2009; Lindsay & Gaskell, 2010; Shtyrov et al., 2010), one may speculate that while predictive facilitation is accessible to younger children, lexical consolidation based on that may not be if these networks are still maturing around 7–8 years of age (Gambi et al., 2021).

There was, however, a difference between the pattern of N400 modulations to prime-target relatedness we report and that of young adults (Borovsky, Elman, & Kutas, 2012). On average, all of our participants showed reliable reductions in N400 modulations to identical/synonymous priming pairs compared to unrelated pairs, similar to young adult data (Borovsky, Elman, & Kutas, 2012). Unlike adult data, children in our investigation showed no reliable N400 modulations for targets of related compared to identical to the prime's meaning, regardless of whether the prime was a word or a pseudoword and regardless of the context it appeared in during the learning phase.

In the context of previous word learning theories, we can conclude that the lack of semantic association between the novel word forms and words of related meaning may reflect incomplete engagement of the novel word forms within our participants' vocabularies (Davis & Gaskell, 2009; Lindsay & Gaskell, 2010). While our older-participant results show that lexical consolidation between the novel word form and its intended meaning had taken place, it appears that full lexical engagement of the novel word form in the lexicon may require multiple learning opportunities (Abel et al., 2018, 2020), more mature cortical structures (Borovsky et al., 2010; Borovsky, Elman, & Kutas, 2012), or both (Gambi et al., 2021; Leach & Samuel, 2007; Shtyrov et al., 2010). Another reason for the null effect may have been methodological: previous semantic priming studies looking into categorical relation development indicate that the strength of the semantic priming effect may be task-dependent (Leach & Samuel, 2007; Perraudin & Mounoud, 2009; von Koss Torkildsen et al., 2006). By using no task during our priming phase blocks, we may have shifted the focus on lexical consolidation of novel word forms, which is presumably more rapid and automatic and away from lexical engagement in participants' vocabularies, which is a slower and more gradual process (Davis & Gaskell, 2009; Lindsay & Gaskell, 2010). Therefore, in line with previous investigations of implicit and explicit word learning in children (Abel et al., 2020), without an explicit task to focus our participants' attention on semantic processing during the priming phase, our experimental setup may have only been sensitive to the explicit associations between the novel word forms (e.g., *fielp*) and their intended meanings (e.g., apple) and not so much to their associations to other related lexical entries (e.g., pear). Furthermore, younger participants may have had lower executive and attentional resources compared to older participants, additionally impeding novel word form consolidation and engagement in their vocabularies after a single exposure. Future investigations manipulating task, presentation mode (visual/auditory), and presentation rate during the priming phase could shed a light on whether one-shot learning truly leads to less intricate semantic network organization of novel words for children compared to adults or whether the lack of secondary task failed to fully explore our participants' novel semantic associations.

5 | CONCLUSION

Our findings indicate that on average 7–13-year-old children learn novel word forms after a single exposure to highly constraining sentences. However, one-shot learning did not come easily to all participants in our sample. Younger preadolescents used sentential constraint to actively predict upcoming continuations, but exhibited weaker semantic association between the presented novel words and the expected meanings. With age, early adolescents showed successful prediction-based one-shot learning and reliable semantic association between novel words and related and synonymous words in their existing vocabulary. In sum, even though both pre- and early adolescents readily used prediction, novel word learning based on these predictions seemed to require resources only available to older children.

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AUTHOR CONTRIBUTIONS

Yoana Vergilova: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; visualization; writing – original draft; writing – review and editing. **Torsten K. Jachmann:** Formal analysis; methodology; validation; writing – original draft; writing – review and editing. **Nivedita Mani:** Conceptualization; funding acquisition; methodology; resources; supervision; writing – review and editing. **Jutta Kray:** Conceptualization; data curation; funding acquisition; methodology; project administration; resources; supervision; validation; writing – review and editing.

CONFLICT OF INTEREST

We declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

Figures, cloze probability pretests, sentence and prime materials, model outputs, and supplementary analyses are openly available at the project's Open Science Framework page (https://osf.io/2cfjd/); [Vergilova et al., 2021].

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

Figure S1

Supplementary S1

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