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## 8 Do Children Use Multi-Word Information in Real-Time 9 Sentence Comprehension? 10

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17

### 18 **Abstract**

19  
20 Meaning in language emerges from multiple words, and children are sensitive to multi-word fre-  
21 quency from infancy. While children successfully use cues from single words to generate linguis-  
22 tic predictions, it is less clear whether and how they use multi-word sequences to guide real-time  
23 language processing and whether they form predictions on the basis of multi-word information or  
24 pairwise associations. We address these questions in two visual-world eye-tracking experiments with  
25 5- to 8-year-old children. In Experiment 1, we asked whether children generate more robust predic-  
26 tions for the sentence-final object of highly frequent sequences (e.g., *Throw the ball*), compared to less  
27 frequent sequences (e.g., *Throw the book*). We further examined if gaze patterns reflect event knowl-  
28 edge or phrasal frequency by comparing the processing of phrases that have the same event structure  
29 but differ in multi-word content (e.g., “*Brush your teeth*” vs. “*Brush her teeth*”). In the second study,  
30 we employed a training paradigm to ask if children are capable of generating predictions from novel  
31 multi-word associations while controlling for the overall frequency of the sequences. While the results  
32 of Experiment 1 suggested that children primarily relied on event associations to generate real-time  
33 predictions, those of Experiment 2 showed that the same children were able to use recurring novel  
34 multi-word sequences to generate real-time linguistic predictions. Together, these findings suggest that  
35 children can draw on multi-word information to generate linguistic predictions, in a context-dependent  
36 fashion, and highlight the need to account for the influence of multi-word sequences in models of  
37 language processing.

38 **Keywords:** Language processing; Multi-word units; Prediction; Visual world paradigm; Eye-tracking  
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## 1. Introduction

Language learners are faced with numerous challenges during spoken language processing: Multiple words unfold rapidly, in a transient signal, while meaning is built incrementally across an utterance. Predictive processing is one cognitive mechanism that is posited to help learners succeed at real-time language processing (Huettig, 2015; Pickering & Gambi, 2018; Pickering & Garrod, 2013). Put simply, prediction during language processing facilitates comprehension by allowing the listener to pre-activate likely linguistic content based on what has already been heard. Listeners use a variety of linguistic cues to support prediction in real time (for a review, see Huettig, Rommers, & Meyer, 2011), and predictive processing skills emerge relatively early in development: Children from at least age 2 can use semantic information from spoken words to restrict the domain of upcoming reference (Gambi, Gorrie, Pickering, & Rabagliati, 2018; Gambi, Jindal, Sharpe, Pickering, & Rabagliati, 2020; Mani & Huettig, 2012), and from 20 months of age, they can exploit prosodic information to unpack the syntactic structure of utterances and predict the upcoming noun/verb (De Carvalho, Dautriche, & Christophe, 2016; De Carvalho, Dautriche, Lin, & Christophe, 2017). Predictive processing is also thought to support language learning processes, with performance on a variety of verbal and nonverbal predictive processing tasks associating with current and future vocabulary skills (Ellis, Gonzalez, & Deák, 2014; Gambi et al., 2020; Reuter, Emberson, Romberg, & Lew-Williams, 2018). Prediction, therefore, seems to play an important role in facilitating language processing and learning early in life; hence, understanding the drivers of these predictive processing skills is necessary to support a full account of language learning and growth. The current project seeks to expand this body of work by exploring whether and how children use their knowledge of multi-word sequences to engage in predictive processing.

Language processing relies on the incremental emergence of meaning as words unfold across a sentence. Crucially, sentence meaning is not based on individual words but on the combination of multiple words, and the information gleaned from such combinations. Studies have shown that adults and children are sensitive to information in multi-word sequences during linguistic production and comprehension. For instance, adults are faster to process higher (vs. lower) frequency multi-word phrases (e.g., Arnon & Snider, 2010; Tremblay, Derwing, Libben, & Westbury, 2011), even in their second language (Hernández, Costa, & Arnon, 2016; Siyanova-Chanturia, Conklin, & Van Heuven, 2011), and are impacted by multi-word frequency in judging phrase complexity and inferring meaning (Reali & Christiansen, 2007). Similarly, young children show higher production accuracy in more frequent phrases (Arnon & Clark, 2011; Bannard & Matthews, 2008), and school-aged children are faster to read more frequent sequences (Jiang, Jiang, & Siyanova-Chanturia, 2020). Sensitivity to multi-word frequency emerges early: 11- to 12-month-old infants prefer listening to trigrams that are frequent in infant-directed input (e.g., “clap your hands”) as opposed to less frequent trigrams (e.g., “take your hands”; Skarabela, Ota, O’Connor, & Arnon, 2021). Beyond this early sensitivity to the *frequency* of multi-word sequences, studies also showed that toddlers are sensitive to the *prosodic features* of such sequences: They utilize them for inferring the meaning of multi-word sequences and for predicting upcoming linguistic content (De Carvalho et al., 2016, 2017). Together, these findings highlight the significance of multi-word sequences for

1  
2 language processing and their role as building blocks in language (Arnon & Christiansen,  
3 2017; Arnon & Cohen Priva, 2013; Arnon & Snider, 2010; Arnon, McCauley, & Christiansen,  
4 2017). Importantly, they suggest that children are sensitive to multi-word information from a  
5 young age. Yet it is not clear whether (and when) children use multi-word information (known  
6 and novel) to generate predictions during real-time language processing—a question that we  
7 address in this paper.

8 In fact, much of the extant evidence for prediction during language processing in children is  
9 based on studies that explore pairwise associations among words, such as when children gen-  
10 erate a prediction for an upcoming noun on the basis of an earlier lexical or morpho-syntactic  
11 cue (Fernald, Thorpe, & Marchman, 2010; Gambi, Pickering, & Rabagliati, 2016; Huang &  
12 Snedeker, 2013; Lew-Williams & Fernald, 2007; Lukyanenko & Fisher, 2016; Zhou, Crain,  
13 & Zhan, 2014). For example, young children can use gendered articles (Lew-Williams &  
14 Fernald, 2007, 2010), selectionally restrictive verbs (Fernald, Zangl, Portillo, & Marchman,  
15 2008; Mani & Huettig, 2012), color adjectives (Fernald et al., 2010), and determiners (Gambi  
16 et al., 2018) to anticipate an upcoming noun. While these studies are immensely valuable in  
17 demonstrating the wide range of (individual) linguistic cues, which drive predictive process-  
18 ing, meaning in language emerges from combinations of multiple words. However, only a  
19 few studies have measured children’s ability to integrate information across multiple words  
20 to guide predictive processing (Borovsky & Creel, 2014; Borovsky, Elman, & Fernald, 2012;  
21 Gambi et al., 2020).

22 For example, Borovsky et al. (2012) found that 3- to 10-year-old children use an infor-  
23 mative agent+action combination (e.g., “The *pirate chases* the —”) to predict the identity  
24 of a highly expected sentence-final object (SHIP). Importantly, children looked at the tar-  
25 get object that was most related to the agent+action combination (e.g., *pirate+chases*) more  
26 than at items that were only related to the agent (TREASURE to pirate) or the action (CAT  
27 to chase). That is, children’s expectations were based on incremental integration of the agent  
28 and the action. A subsequent study suggested that children aged 5–10 years could also gen-  
29 erate real-time predictions for recently learned events, which were expressed in novel com-  
30 binations of known agents and actions (Borovsky, Sweeney, Elman, & Fernald, 2014). For  
31 example, after hearing a story that included multiple novel events (e.g., a monkey that rides a  
32 bus and eats candy), in a subsequent eye-tracked sentence comprehension task, children gen-  
33 erated more anticipatory looks toward the target BUS in the sentence context “*The monkey*  
34 *rides ...*” than toward other distractor images that were action-related (i.e., *car*), agent-related  
35 (i.e., *candy*), and unrelated (i.e., *apple*) even though the “*monkey riding a bus*” association is  
36 not predictable from the child’s prior linguistic and world experience (Borovsky et al., 2014).

37 Hence, children seem to generate predictions toward a sentence-final target (e.g., *ship*)  
38 based on their knowledge of the associations between the elements that precede it (e.g.,  
39 *pirate-chase*), but it is not clear whether the distributional properties and frequency of the  
40 entire multi-word sequence (e.g., *pirate-chase-ship*) inform these predictions (Borovsky et al.,  
41 2012). Similarly, children’s ability to predict the target in novel agent+action combinations  
42 may have been the result of computing pairwise statistics (Borovsky et al., 2014). In this  
43 latter study, children were exposed to novel events that involved two agents (e.g., a mon-  
44 key and a dog), who completed two actions (e.g., riding and eating) on different objects

2 (e.g., bus, car, candy, apple). Because children were then subsequently tested on the asso-  
3 ciations that appeared in the story (e.g., in one version of the learning phase, the monkey  
4 agent was paired with riding a bus and eating an apple), it is not possible to distinguish  
5 between a prediction based on paired lexical associations and one based on multi-word infor-  
6 mation (where the entire trigram is represented). In sum, the evidence we have to date does  
7 not allow us to ascertain whether and how children rely on the frequency of known and newly  
8 learned multi-word information for predictive processing. The two experiments reported here  
9 directly extend and expand previous work and address the gap in the literature by examining  
10 whether 5- to 8-year-olds generate expectations in real-time processing based on multi-word  
11 sequences or whether they rely only on pairwise associations. Importantly, our definition of  
12 multi-word sequences *does not* refer to lexicalized wholes (in the age range we are test-  
13 ing, children have probably already analyzed sequences into individual words) or to abstract  
14 frames with slots. Instead, we use the term multi-word sequence to refer to the associations  
15 formed between multiple individual words resulting in a representation of the entire sequence  
16 alongside its parts.

17 In the first experiment, we asked if children rely on the frequency and familiarity of fre-  
18 quent frames (multi-word sequences that are frequently present in child-directed language  
19 input) to anticipate upcoming nouns using a visual world task. Using a design similar to that  
20 of Arnon and Clark (2011), we present children with trials in which they see a target object  
21 (e.g., *teeth*), and a distractor (e.g., *hair*) and then hear a stimulus sentence (e.g., *Brush your*  
22 *teeth*). Participants are exposed to four experimental conditions in which we manipulate the  
23 frequency of the object at the end of the frame, changing the *frequency* of the entire frame  
24 (high, low: e.g., high frequency: “*Brush your teeth*” vs. lower frequency: “*Brush your hair*”),  
25 and the item in the middle of the frame changing its *familiarity* or *type* (familiar, modified:  
26 e.g., familiar: “*Brush your teeth*” vs. modified: “*Brush her teeth*”). Our question here focuses  
27 on children’s sensitivity to the associations between the three words as opposed to the event  
28 associations (represented by the verb–object association), and our main aim is to determine  
29 whether children’s prediction of the target object is impacted by the frequency of the entire lin-  
30 guistic frame in which the object is presented. We specifically compare gaze to the target and  
31 distractor across the experimental conditions. If children rely on multi-word frequency, then  
32 we should expect to see more accurate prediction of the target object in the high-frequency  
33 frames, compared to the low-frequency frames; children should be more accurate in gener-  
34 ating such predictions following familiar frames as opposed to modified ones. However, if  
35 children only rely on event associations for prediction (e.g., the association between *brush*  
36 and *teeth*), then we should not see any differences between the familiar and modified frames  
37 and should observe differences only between the high- and low-frequency frames.

38 In the second experiment, run on the same children, we employ a training paradigm to  
39 ask if children are capable of rapidly forming novel multi-word associations and using these  
40 associations in predictive processing. This study allows us to better distinguish the effect of  
41 pairwise associations from that of multi-word frequency (by carefully controlling for both  
42 in the training data) while also asking whether such associations are created after a rela-  
43 tively short exposure and then used in real-time processing. Using a design similar to that of  
44 Borovsky et al. (2014), we expose children to stories in which we vary the frequency of the

agent–action–object trigram (e.g., monkey–ride–bus) while controlling the frequency of the agent–action bigram (monkey–ride) and the action–object bigram (ride–bus), by presenting events that highlight both the trigram and bigram associations. For example, some portions of the story will present the trigram relation (monkey–riding–bus), while others will increase the frequency of the component/alternate bigrams (riding–car). Children are then tested in a sentence recognition task, in which they are asked to identify the object that goes with the sentence. Here too, we compare children’s gaze to the target and distractor images as the sentence unfolds. We hypothesize that children would rely on the agent–action–object relations they learned from the stories and generate anticipatory looks toward the target of the sentence before it is mentioned. The design of this experiment allows us to isolate the effect of multi-word frequency from that of event frequency in a way that is hard to do in natural language and that can shed light on children’s representation of combinatorial multi-word information.

Identifying whether and how children rely on the frequency of multi-word sequences in real-time language comprehension has several theoretical implications. First, these findings would enrich our understanding of the kind of information that guides predictive processing in children. While some proposals framed by evidence derived from adult processing studies suggest that predictive processing involves multiple potential mechanisms (that rely on production, association, probabilistic knowledge, and more, see Pickering & Garrod, 2013), others have argued that these accounts may not translate directly to younger children with alternating evidence for and against (pairwise) associative mechanisms in prediction (Mani & Huettig, 2013; Mani, Daum, & Huettig, 2016), suggesting that children may recruit statistical information about word sequences to guide predictive processing in a context-dependent fashion. If children track the frequency of both words and larger sequences, then models of processing should account for multi-word representations across development. Second, finding that processing is guided (among other factors) by multi-word frequency would support the role of larger units as building blocks in the language (Arnon & Clark, 2011; Arnon et al., 2017; Bannard & Matthews, 2008) and would be consistent with single-system models of language where all linguistic experience, whether words or larger phrases, is processed and represented using a single cognitive mechanism that compiles frequency at multiple levels of experience (e.g., Bybee, 1998; Elman, 2009; McClelland et al., 2010). Alternatively, if the outcomes of both studies suggest that children generate predictions based only on individual or pairwise associations, this would cast doubt on the role of larger sequences in children’s online processing. Either way, our results will add valuable and much-needed evidence to the work examining the cues and information used in real-time processing during development.

## 2. Experiment 1

### 2.1. Methods

#### 2.1.1. Participants

Thirty-seven children between the ages of 5 and 8 years participated in the study (see details on sample size justification in Section 2.1.2). Families were recruited from a

recruitment registry at Florida State University, which includes a list of families with children from the surrounding community who expressed interest in participating in developmental research. Families with children within the desired age range were invited to take part in a study at the Florida State University Language and Cognitive Development Laboratory. Inclusionary criteria were: (1) native English-speaking and not hearing more than 20 h a week at home of a language other than English, (2) normal or corrected-to-normal vision and normal hearing, (3) has not received treatment for any speech, language, reading, or cognitive concerns. Two participants failed to meet these criteria: One parent reported a reading-related issue, and another reported a diagnosis of ADHD. One participant was not included in the analyses due to an equipment issue that led to the failure to collect eye-tracking data. A total of 34 participants were therefore included in the final sample. All child participants' parents provided written consent, and the experimental procedures were reviewed and approved by the local institutional review board at Florida State University under the following IRB protocol # 2016.18919 "Development of Language Processing Skills."

### 2.1.2. *Sample size justification*

Our target sample size ( $N = 32$ ) was based on previous predictive processing studies (our recruitment strategy led us to overshoot slightly, and we ended up with a slightly larger sample,  $N = 34$ ). To ensure that our sample size was adequately powered to detect effects in our study, we have carried out several post hoc power analyses using the *simR* package in R for linear mixed effects modeling (Green & MacLeod, 2016). These analyses suggested that our experiments were adequately powered. The simulation approach in this package is appropriate for a variety of experimental designs using linear mixed effects modeling as we have used. We used this package to determine whether our sample size ( $N = 34$  participants included in the final analyses) was sufficient with at least power = 80% to detect a (medium) fixed effect size of 0.20 in both experiments. For Experiment 1, this analysis indicated that we had at least 99% power to detect a main fixed effect of this size, and 97% power to detect an interaction. For Experiment 2, the analysis similarly indicated 100% power to detect a (medium) fixed effect of interest area of size = 0.2.

### 2.1.3. *Stimuli*

**2.1.3.1. *Sentence selection:*** Three word sequences of the form "verb-(pronoun/article/preposition)-object" were selected for the study using a large subset of the CHILDES database (MacWhinney, 2000). We used all the speech directed to children under the age of 6 who are learning American English (around 6 million words). We extracted all the trigrams starting with a set of early acquired and highly frequent verbs (based on the MacArthur-Bates Communicative Development Inventory; Fenson et al., 2007): *brush, close, drink, open, throw, want, wash*. For each verb, we then selected two sentence frames: one that contained a more frequent object completion (e.g., "Close your *eyes*") and one that contained a less frequent object completion (e.g., "Close your *mouth*," see Appendix A for the full list of sentence frames). All objects were highly frequent in the corpus (mean frequency of 578 per million words), and all frames were plausible. For example, "*Brush your teeth*" is more

Table 1  
Means and standard deviations for all frequency information for the stimuli in Experiment 1

Type	Frame Frequency <i>M</i> ( <i>SD</i> )	Object Frequency <i>M</i> ( <i>SD</i> )	Verb–Object Frequency <i>M</i> ( <i>SD</i> )
FF-High	22.785 (13.98)	476.57 (288.16)	34.141 (18.825)
FF-Low	3.071 (2.07)	680.356 (433.528)	12.046 (9.405)
MF-High	1.308 (1.171)	476.57 (288.16)	34.141 (18.825)
MF-Low	1.475 (1.295)	680.356 (433.528)	12.046 (9.405)

*Note.* Counts are extracted from a mega-corpus (~6 million words) of American English in naturalistic interactions with typically developing children between the ages of 2–6 years. Numbers represent the frequency per 1 million words. *Frame Frequency* refers to the frequency of the entire three-word frame (e.g., “Brush your teeth”), *Object Frequency* is the number of times the noun in the frame appeared on its own, and *Verb–Object Frequency* counts the occurrence of the verb and object with any intervening item (how often “Brush X teeth” occurs).

Abbreviations: FF-High, familiar frame–high frequency; FF-Low, familiar frame–low frequency; MF-High, modified frame–high frequency; MF-Low, modified frame–low frequency.

frequent than “*Brush your hair*,” but both are feasible sentences that could be spoken to young children as verified by their appearance within the CHILDES corpus. Both high- and low-frequency frames were assigned to the familiar frame condition. We then created sentences for the modified frame condition by changing the intervening element (pronoun, article, or preposition) in each of the items classified as familiar frames to another item that would still result in a plausible sentence/event (e.g., “brush *his* hair/teeth”) but one that rarely appeared in the same child-directed corpus (mean frequency of 1.5 per million). Modified frames were created to directly compare against the familiar frames as a test of whether processing in the high- and low-frequency condition is driven by the multi-word sequence that precedes the target noun or simply by the association between the object and the event denoted by the verb.

Together, this arrangement yielded four experimental conditions that varied by frame type (familiar or modified) and frame frequency (high or low): (1) familiar frame–high frequency (FF-High; e.g., *Close your eyes*), (2) familiar frame–low frequency (FF-Low; e.g., *Close your mouth*), (3) modified frame–high frequency (MF-High; *Close his eyes*), and (4) modified frame–low frequency (MF-Low; *Close his mouth*). Sentences falling under the FF-High and MF-High conditions had the same mean object frequency and verb–object frequency as seen in Table 1 but had different frame frequency. Similarly, sentences classified as FF-Low and those classified as MF-Low shared the same mean object frequency and verb–object frequency but differed in the frame frequency. Importantly, as seen in Table 1 and Appendix A, the modified frames (both high and low) have similar low frequencies, that contrast with the frequencies of the familiar frames. The goal behind creating these modified frames from the original familiar frames was to try to tease apart the effects of the verb alone on the prediction of the object as opposed to the verb+pronoun. See Appendix A for a list of all sentences in all conditions along with associated frequency counts for each sentence type.

2 2.1.3.2. *Visual stimuli:* Colorful, photorealistic images of all experimental sentence-final  
3 objects were selected. For each image, any extraneous background information was removed,  
4 and the remaining image was centered on a white background of  $400 \times 400$  pixels. Several  
5 additional images were either used to direct the child's attention to the center of the screen  
6 (e.g., a small flower or star) or to provide longer breaks and encouragement during the study  
7 (e.g., a scene containing the characters from *Finding Nemo*).  
8

9 2.1.3.3. *Auditory stimuli:* All spoken items were recorded in a child-directed voice by a  
10 native American English-speaking female. Auditory stimuli were sampled on a mono channel  
11 at 44,100 kHz sampling rate. Praat software (Boersma & Weenink, 2012) was used to align  
12 the critical onsets across stimuli. Sentences were adjusted to an overall duration of 1655 ms,  
13 with the following durations for each word: verb–693 ms, pronoun/article/preposition–379  
14 ms, noun–583 ms. The intensity of all stimuli was adjusted to a mean of 70 dB. The speaker  
15 also recorded several additional encouraging phrases to be used to maintain child attention  
16 during the experiment.  
17

#### 18 2.1.4. *Procedure*

19 Children were seated in a stationary chair in front of a 17-inch LCD monitor with an  
20 attached eye-tracking camera. The monitor was attached to a remote arm mount so that the  
21 height and distance of the camera could be adjusted specifically to the child. The eye-tracking  
22 camera was positioned between 580 and 620 mm from the child's eyes. Auditory stimuli were  
23 presented via child-size headphones, and the experimenter did not hear the sentences. This  
24 set-up also insured that the auditory stimuli did not influence the experimenter's judgment of  
25 the child's responses.  
26

27 Before the start of the experiment, children were told they would hear some sentences and  
28 would be asked to point to images that were depicted on the screen that went along with these  
29 sentences. They were given a single example trial where they heard a sentence and pointed  
30 to a picture. No children required additional explanation after this step, and the eye-tracker  
31 was then calibrated using a standard five-point calibration routine. Children generally viewed  
32 these calibration stimuli without additional instruction, but the experimenter did occasionally  
33 remind the child to direct their gaze toward the calibration images.

34 Next, the experimental trials began. Each trial started with the presentation of a drift-check  
35 image (a 20-point black-and-white bull's eye image) to ensure the child was attending to  
36 the screen before the onset of the experimental trial and that the calibration was maintained  
37 throughout the course of the experiment. Next, the target (e.g., *teeth*) and distractor (e.g., *hair*)  
38 images appeared in silence for 2000 ms, followed by the appearance of a gaze-contingent  $100 \times 100$   
39 pixel center image as the sound "Look!" was played. This central image remained on  
40 the screen until the tracker detected that the child fixated within the  $100 \times 100$  pixel bounds  
41 of the image for 100 ms. Then, the sentence stimulus was spoken (e.g., *Brush your teeth*),  
42 and the images remained on the screen until the child pointed toward one of the images, and  
43 the experimenter used the computer mouse to click on the child's selection. See Fig. 1 for an  
44 illustration of an experimental trial.

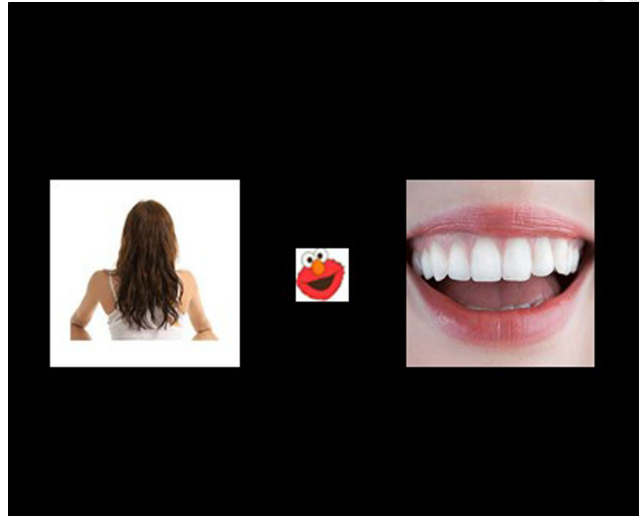


Fig 1. An example of an image used during the visual-world paradigm sentence recognition task.

Each image appeared four times across the study, twice as the target and twice as the distractor. Each image appeared on the left and right sides with equal frequency across trials. With 14 target–distractor image pairs, this yielded 28 total experimental trials (14 in the familiar frame condition and 14 in the modified frame condition) that were presented in four blocks of seven trials each. Trials were equally distributed across all conditions in the study and presented in pseudo-random order, such that no single condition appeared in more than two sequential trials. Each participant, therefore, contributed equally to all conditions of the study, yielding a completely within-subjects design. Between each block, children saw filler trials that contained images of smiling animals or popular cartoon characters. Children usually completed the entire experimental procedure in less than 10 min.

*2.1.4.1. Eye-movement recording:* Children's eye movements were recorded at 500 Hz as they viewed the experimental trials using an SR-Research EyeLink 1000+ eye tracker. Areas of interest were pre-defined as the two  $400 \times 400$  pixel regions comprising the target and distractor images. Data were collated into 50 ms bins for offline analysis.

*2.1.4.2. Eye-movement data analysis:* Our primary analyses address whether and when children used the first two words of the multi-word frames (verb + pronoun/article/preposition) to generate fixations toward the target object. Our analyses sought to determine whether recognition of the target object varied as a function of frame frequency (high and low) and frame type (familiar and modified) and specifically whether these fixations were anticipatory in nature. As in prior work (Borovsky et al., 2012; Kamide, Altmann, & Haywood, 2003), we consider conditions where looks to the target object exceed those to the distractor before the onset of the spoken target word as strong evidence for anticipatory

2 activation of the target item. Despite the straightforward nature of this criterion for prediction,  
3 there is substantial variability in the eye-tracking field regarding precisely how predictive fixa-  
4 tions should be measured. Here, we take two approaches that quantify eye-movement behav-  
5 ior over relatively broad and fine-scale time windows as described below. First, we assess  
6 predictive effects using a broad time-window analysis spanning the time window from verb  
7 onset to noun onset (i.e., the anticipatory period before the onset of the spoken target noun).  
8 In this broad time window, we measured the overall accuracy of prediction of the target as a  
9 proportion of fixations toward the target divided by the total looks toward the target and dis-  
10 tractor. This accuracy measure was selected as it is commonly used in studies of lexical devel-  
11 opment (see Swingley, 2011, for a review). This broad time-window analytical approach has  
12 been commonly implemented in the developmental eye-tracking literature and summarizes  
13 looking behavior over a relatively long time window spanning several hundred milliseconds.  
14 However, this approach can overlook more rapid fixation phenomena that are captured by the  
15 high sampling rate of modern eye-tracking equipment. To investigate these rapid processes,  
16 we use a non-parametric cluster test procedure that can characterize the timing and duration of  
17 a preference to view the target image while controlling for multiple comparisons (see Groppe,  
18 Urbach, & Kutas, 2011; Maris & Oostenveld, 2007, for expanded description and tutorials on  
19 this method). This cluster-based permutation procedure has been already implemented in the  
20 developmental eye-tracking literature (Borovsky, Ellis, Evans, & Elman, 2016; Von Holzen &  
21 Mani, 2012), and we use it here to identify time windows across the sentence where fixations  
22 toward the target significantly exceed those to the distractor object. If the target divergence  
23 point begins before the onset of the spoken target, this is taken as evidence for predictive  
24 processing.

25 The basic procedure for this non-parametric cluster-based permutation test is as follows:  
26 First, the procedure is used to identify “clusters”—defined as temporally adjacent time points  
27 in the dataset where the statistical difference (by  $t$  test) is significantly different (at  $\alpha =$   
28 0.05 threshold). The  $t$ -statistics of these clusters are summed to create a cluster  $t$ -statistic.  
29 These cluster  $t$ -statistics are then compared to randomly permuted  $t$ -statistic distribution of  
30 the same dataset (following the permutation approach outlined in Barr, Jackson, & Phillips,  
31 2014, Appendix).

32 Finally, we wished to verify that the trials we included in the analyses were those in which  
33 children were attending to the auditory and visual stimuli. First, we removed trials in which  
34 children selected the incorrect target picture. This resulted in the removal of 31 trials (out of  
35 952 total or 3.26% of total trials) with incorrect target selections, leaving 921 total correct  
36 trials to be entered into subsequent analyses. Second, we sought to identify trials in which  
37 children were not visually attentive to the screen during the time window of analysis. Thus,  
38 we removed trials in which children did not view the target or distractor picture for more than  
39 25% of the analyzed time window. This led to the removal of 10% of the remaining trials (92  
40 out of 921 correct trials, with 829 trials remaining in the final analyses) from the broad time-  
41 window analysis, which was limited to the anticipatory time window. For the finer-grained  
42 cluster analysis involving the entire sentence time window, this track loss threshold led to the  
43 removal of 8.9% of the remaining trials (82 out of 921 correct trials, with 839 remaining in  
44 the final analyses).

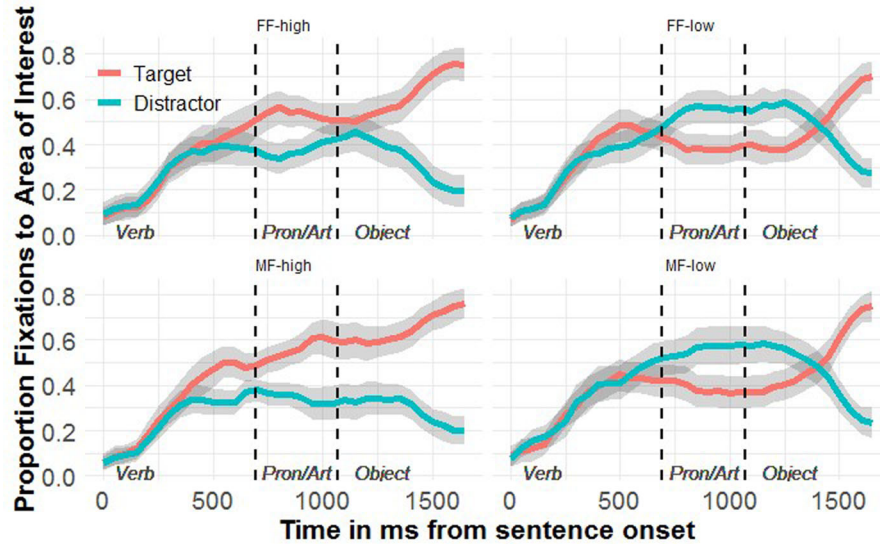


Fig 2. Time-course of proportion fixations to target and distractor images across experimental conditions. Note. Error cloud represents confidence intervals (CIs). Lines mark word onsets.

## 2.2. Results

Fig. 2 illustrates the time-course of fixations toward the target and distractor images across the spoken sentences in the four experimental conditions (FF-High, MF-High, FF-Low, MF-Low). This figure illustrates an expected increase and divergence in fixations toward the target relative to the distractor as the sentence unfolds.

### 2.2.1. Experimental effects on target fixations during a pre-determined anticipatory time window

To explore whether we find broad evidence for predictive looking and if this interacted with frame type or frame frequency, we calculated mean accuracy for each experimental condition as a proportion of fixations toward the target relative to the distractor over the entire anticipatory time window from verb onset to noun onset (Fig. 3; data for individual children can be seen in the line graphs in Fig. 4). Using the lme4 library (Bates, Maechler, Bolker, & Walker, 2015) in the R environment (R Core Team, 2016), we fitted a linear mixed effects regression model to test for differences in accuracy as a function of frame type and frame frequency. We additionally included fixed-effect factors of age (in months) and trial number (centered) in the model. For random effects, we began with a full model that included by-item and by-subject random intercepts, along with a by-subject random slope of experimental condition; however, this model did not converge, and so we iteratively simplified the random effects by removing those that explained the least variance, starting with removing the slopes, until the model did converge (final model:  $Accuracy \sim Frame\ Type * Frame\ Frequency + Trial\ Order + Age + (1 | Items)$ ; see Table 2; a more detailed version

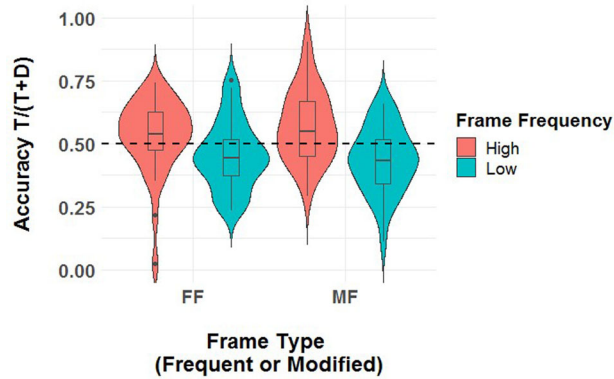


Fig 3. Fixation accuracy during the anticipatory time window by condition across all participants in Experiment 1.

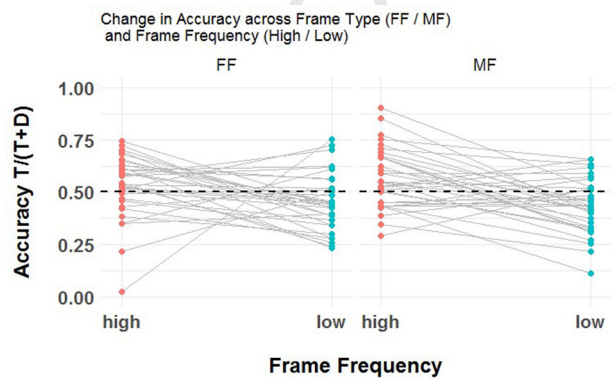


Fig 4. Change in accuracy during the anticipatory time window across frame frequency (high/low) in each of the frame types (familiar frame, modified frame) for all participants in Experiment 1. Note. The dotted horizontal line at 0.5 indicates equivalent looking toward the target and distractor.

of Table 2 that includes random effects is available in the Supplementary Materials, Section 7.1). We also compared this final model to a model with the same fixed effect structure and no specified random effects, and there was a marginally significant improvement in fit ( $LR = 3.59, p = .058$ ).

As is evident from Fig. 3 and Table 2, we found a significant effect of frame frequency on performance: Children view objects that occur in high-frequency frames during the anticipatory time window to a greater extent than objects that occur in low-frequency frames. However, we did not find evidence for a statistically significant effect of frame type on the prediction of the target object. We also did not observe evidence for a significant interaction between frame type and frame frequency (see Fig. 1 in the Supplementary Materials, Section 7.2, in which we collapse frame types into one group and present proportion of fixation to the target and distractor only as a function of the frequency of the frame, i.e., high vs. low). These results suggest that these effects are likely to be driven by the association between

Table 2  
Regression model for Experiment 1

Effect/Slope	Estimate	Confidence interval (CI)	<i>t</i> -value	<i>p</i> -value
<b>(Intercept)</b>	<b>0.496</b>	<b>0.461–0.531</b>	<b>27.672</b>	<b>&lt; .001</b>
Frame type	−0.006	−0.077–0.064	−0.179	.861
<b>Frame frequency</b>	<b>0.122</b>	<b>0.072–0.172</b>	<b>4.778</b>	<b>&lt; .001</b>
Type x Frequency	−0.056	−0.156– 0.043	−1.110	.268
Age	0.004	−0.020–0.029	0.342	.733
<b>Trial order</b>	<b>−0.031</b>	<b>−0.059–0.003</b>	<b>−2.202</b>	<b>.029</b>

*Note.* The model summary including random effects is listed in Supplementary Materials, Section 7.1.

the verb and the sentence-final object rather than the sentence frame per se. Further, we did not find a significant effect of age on performance, but we found a significant effect of trial order, with a negative beta-estimate indicating that performance declined over the course of the experiment, suggesting that some fatigue effects may have influenced performance across the study. Importantly, this result suggests that children did not adapt their performance to generate more predictive fixations across the experimental trials.<sup>1</sup>

### 2.2.2. *Finer-grained time-course analysis*

Analysis of fixations over broad time windows can sometimes mask effects that occur over much shorter timescales. Therefore, our next analytical goal was to explore whether the timing of target divergence varied as a function of the experimental condition using a cluster-based permutation analysis as described above. In this analysis, we initially calculated a dependent measure of target looking relative to that of the distractor item as a log-gaze proportion ratio in each time window that defines the bias of looking toward the target or distractor on a scale from negative to positive infinity, centered around 0 (see Arai, Van Gompel, & Scheepers, 2007; Borovsky et al., 2016, for a similar approach and additional explanation). These values were then used to generate fine-grained comparisons of fixations across experimental conditions. We initially compared log-gaze ratios as a function of frame frequency in the familiar and modified conditions separately to determine whether and when frequency influenced looking as a function of frame frequency in each frame condition. Next, we compared log-gaze ratios in high and low frame frequency conditions as a function of frame type (modified or familiar) separately to explore whether there were timing differences in looks toward that target as a function of frame type in each frame frequency condition. The results of these cluster analyses are outlined in Table 3 and support the findings of the broad time-window analyses. When comparing differences between high and low frequency in familiar and modified frames separately, significant differences emerge starting in the anticipatory time window and continue until approximately 100 ms before sentence offset, when participants begin to look away from the target object. No cluster-based differences emerge when comparing familiar and modified frames in each of the frequency conditions, supporting prior analysis that did not find any main or interaction effects involving frame type.

Table 3  
Timing differences identified by cluster-based permutation analyses in Experiment 1

Comparison	Time window
Familiar frame High versus low	750–1550 ms ( $t = 47.03, p < .0001$ )
Modified frame High versus low	800–1550 ms ( $t = 57.05, p < .0001$ )
High frequency Familiar versus modified	No clusters identified
Low frequency Familiar versus modified	No clusters identified

*Note.* Timing is measured from the onset of the spoken sentence, which was 1655 ms in duration. The time window where looking at the target significantly exceeded that to the distractor is reported in ms, followed by the cluster  $t$ -statistic and Monte Carlo  $p$ -value for that window, in parentheses. The onset of the sentence-final target was at 1070 ms post sentence onset.  $p$ -values are Bonferroni-corrected.

### 2.3. Discussion

Using the visual world paradigm and a design inspired by prior language production work (Arnon & Clark, 2011; Bannard & Matthews, 2008), we sought to examine whether and how children utilize multi-word information during online speech processing and whether they form linguistic predictions based on multi-word associations. Specifically, we examined whether children are sensitive to the associations between multiple words in a sequence frequent in their input (e.g., *Brush your teeth*) or only to the event associations reflected in the verb–object relationships (e.g., *brush–teeth*, *brush–hair*), a contrast that was not directly tested in previous research. We asked whether children would be faster to anticipate sentence-final objects in higher-frequency frames, compared to less frequent ones (e.g., *Brush your teeth* vs. *Brush your hair*), and whether gaze patterns to high-frequency frames reflect event knowledge or real-time summation of phrasal frequency using modified frames (e.g., *Brush her teeth* vs. *Brush her hair*). We found that children generated a stronger prediction for the object in higher frequency sequences (*Brush your teeth* vs. *Brush your hair*) even when both outcomes were highly plausible (*hair* and *teeth* are both “brush-able”). However, when the event remained constant while the frame was modified by a single word, rendering those modified sequences less frequent in the input (*Brush your teeth* vs. *Brush her teeth*), children were equally likely to predict the higher frequency ending of the frame regardless of whether it was modified or not. These findings suggest that children relied primarily on the frequency of the verb–object associations for prediction and do not provide evidence for children’s use of multi-word information during online processing.

There are several possible explanations for our findings. First, it is possible that our results are driven by children’s knowledge of abstract frames with varying levels of productivity in the different slots rather than non-adjacent verb–object associations. Specifically, the intervening element (pronoun, article, or preposition) in each of the frames we used is much less productive as an abstract slot, compared to that of the noun at the end of the frame (i.e., there are a lot more options that can be used in the noun slot as opposed to the middle slot);

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2 slots that are more productive end up being organized around the most frequent items (*teeth*  
3 may act as a prototype for the noun slot in a frame that begins with *brush*; Bybee, 2006). Such  
4 difference in the productivity of the slots may have led children to represent multi-word infor-  
5 mation that relies on abstract representations rather than multi-word associations (*brush* may  
6 be followed by a lot of nouns, and there are a few options for what may intervene between  
7 them; *teeth* is the prototypical option and is preferred over other options). Unfortunately, the  
8 current design does not allow us to examine the impact of slot productivity, as our stimuli did  
9 not systematically vary on this dimension. Only future work can help address this issue.<sup>2</sup>

10 Second, it is possible that the brief duration of the intermediate element between the verb  
11 and the object did not provide enough time for children to modify their expectations for  
12 the sentence-final object. The spoken pronoun/article/preposition had an average duration of  
13 379 ms, only a little longer than the 250–350 ms range during which children in this age  
14 group (Trueswell, Sekerina, Hill, & Logrip, 1999) and adults (Matin, Shao, & Boff, 1993)  
15 show a divergence in their eye movements in response to linguistic stimuli. Many visual  
16 world paradigm designs incorporate intervening items, such as adjectives that allow time  
17 for eye movements to unfold for this very reason. Additionally, these intermediate elements  
18 carried only minimal (if any) semantic content that the listener could leverage to generate an  
19 anticipatory fixation. It is, therefore, possible that the particular structures that we selected  
20 for this experimental manipulation were not ideal to observe the phenomenon of interest and  
21 that the predictive processes in question unfold over a slower timescale than the duration of a  
22 mono-syllabic article, pronoun, or preposition.

23 Third, given that we relied on naturalistic variation in frame frequency, it is possible that  
24 the frequency differences between the high- and low-frequency frames across the conditions  
25 (i.e., the difference between the frequency of FF-High and MF-High and between FF-Low  
26 and MF-Low) were not large enough to modify fixation behavior and influence language pro-  
27 cessing and hence result in an interaction effect between frame frequency and frame type.  
28 However, the number of naturally occurring trigrams that we could feasibly incorporate into  
29 this design was limited; therefore, it is possible that our items may not have provided a strong  
30 enough manipulation to drive differences in eye movements. This possibility has been recently  
31 attested in a study that examined children's fixations to a target upon hearing word bigrams  
32 that varied in their frequency (Jones, Cabiddu, & Avila-Varela, 2020). The results showed that  
33 children's fixations appeared to be influenced by the categorical presence or absence of the  
34 bigram in child-directed speech and by the graded changes of frequency, such that bigrams  
35 that appeared an average of 19 times per million words and those that appeared an average  
36 of 206 times were processed in a similar manner by 2-year-olds. Hence, it is likely that the  
37 range of frequencies of our frequent frames (see Appendix A) was not large enough to capture  
38 differences in processing. Finally, it is theoretically possible that the impact of multi-word fre-  
39 quency on processing that has been previously attested in adults' comprehension (e.g., Arnon  
40 & Snider, 2010; Hernández et al., 2016; Reali & Christiansen, 2007; Siyanova-Chanturia  
41 et al., 2011; Tremblay et al., 2011), and children's productions (Arnon & Clark, 2011; Ban-  
42 nard & Matthews, 2008) does not impact children's comprehension of spoken language and  
43 that during online language processing, children do not rely on the frequency of multi-word  
44 sequences.

Further information that can aid in interpreting these results may be gleaned from the next experiment. Experiment 2 was designed to better distinguish between the impact of pairwise associations and multi-word frequency and to examine whether children can learn novel multi-word frequencies from a short exposure and use them in predictive processing. We utilized a training design that allowed us to control the frequency of multi-word associations by presenting learners with novel events described using multi-word sequences. The second study also included longer intervening durations between the informative items in the frame and the sentence-final outcome. This design allows us to shed additional light on children's reliance on multi-word frequency during online processing.

### 3. Experiment 2

#### 3.1. Methods

##### 3.1.1. Participants

The same children who participated in Experiment 1 were also invited to take part in Experiment 2 during the same laboratory visit. Participants always completed Experiment 1 before being asked if they would like to continue to Experiment 2. All children agreed to participate in the second task.

##### 3.1.2. Stimuli

**3.1.2.1. Story materials:** Participants heard four sets of stories (eight stories), such that each one conveyed novel events comprising relationships among two agents, two actions, and four thematic objects (two per action). Stories were presented on a computer, with each "page" in the story corresponding to a colorful cartoon image (400 × 400 pixels in size). These images were created using the comic strip creation website, Toondoo (<http://www.toondoo.com>). Each image in the story was accompanied by spoken narration that reinforced the visually depicted events in the story. The narration was pre-recorded by a native English-speaking female at 44.1 kHz on a mono channel and normalized to a mean intensity of 70 dB.

The goal of each narration was to develop combinatorial (agent–action–object) and associative (action–object) relations that were equivalent in frequency. Therefore, the stories followed a narrative structure similar to that used in Borovsky et al. (2014) with several key modifications. Like in prior work, each story described actions carried out by two different agents (e.g., a monkey and a dog), who each performed two different actions (e.g., riding and eating) on different objects (see Appendix B for a list of all agent–action–object combinations used in the experiment). These narrative associations served to establish four main combinatorial relations among the two agents, two actions, and four objects in the story set. Crucially, in the current task, listeners also viewed two additional action–object relations in sentence frames that did not mention either of the agents (e.g., ride–bus and eat–apple, see Fig. 5). This additional action–object association served to level the summed association frequency for two of the four combinatorial relations in the story. More concretely, consider the example

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*Look there's a  
monkey!**What's that? He's  
riding in the bus!**What's he doing  
now? He's eating  
the candy. What a  
silly monkey!*

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*Hey there's an apple!  
Let's eat the apple.**Look there's a bus!  
Let's ride in the bus.**Look, there's a dog!**What's that? He's  
eating the apple.**What's he doing  
now? He's riding in  
the car. What a silly  
dog.*

Fig 5. Example of images and accompanying spoken narration from Experiment 2.

in Fig. 4. Here, the child's prediction following a sentence like "*The monkey rides in the...*" has two potential outcomes depending on how the child uses the frequency information in the story. One possibility is that the child may have attended to all pairwise frequencies across the story. This option would suggest that the child should not generate a specific expectation for BUS or CAR when hearing the sentence "*The monkey rides the...*" since ride-bus and ride-car appeared with equal frequency in the story (twice each). However, if the child computes frequencies at the level of the trigram (*monkey-ride-bus*, which appears only once), in addition to pairwise relations, then the statistics of the story would lead the child to specifically expect BUS after hearing the sentence.

As illustrated in Fig. 5, the events in each story were presented in identical order across each of the eight stories in the experiment. First, the narrator introduced one of the agents (e.g., MONKEY, *Look! there's a monkey*), and two specific event associations are established for that particular agent (e.g., riding in a bus, eating a candy). Next, the listener heard two events described that are not associated with a novel agent, one object that was associated with the first introduced agent (*Let's ride in the bus*) and a second that corresponds to the next-to-be introduced agent (*Let's eat the apple*). Finally, the second agent appears (e.g., DOG, *Look! there's a dog*), along with two novel event associations (e.g.,

riding in a car, eating an apple). The event relations were counterbalanced across versions of the experiment such that all potential combinations of the agent–action–object appeared across versions. For example, in one version, a dog may have eaten an apple and have ridden in a car, while in another version the dog may have eaten a candy and have ridden in a bus. Even though the goal of constructing these cartoon narratives was to develop very low-frequency events that participants were unlikely to have previously encountered in the world, this counterbalancing served as extra insurance against the possibility that participants may have had pre-existing biases to prefer certain constructed event combinations over others.

It should additionally be mentioned that, as in prior work with similar stimuli, the verbal description of the event relations never explicitly mentioned all of the elements of the event in the same sentence. For example, in the dog—rides—car example, the narration indicated that the dog was present in one scene in the story, and then later the narration conveys that *He's riding in the car*, but the narration never stated verbatim that *The dog is riding in the car*. The goal was to prevent the learner from hearing the same acoustic stimulus during the story phase that was presented in the sentence recognition phase of the experimental task. It should also be noted that because the combination of the event relations was controlled across versions, this arrangement further ensured that the same acoustic signal during the narration conveyed the same event relation for all agents across versions (i.e., The same auditory file was used to describe *He's riding in the car*, for both the dog and the monkey across the separate experimental versions where each agent performed this action).

**3.1.2.2. Sentence recognition stimuli:** Each story was followed by a visual world sentence recognition task that was designed to measure the real-time recognition of the two critical combinatorial relations from the story. Participants initially viewed four objects on the monitor. These four images consisted of the thematic objects that initially appeared in the prior story (e.g., BUS, CAR, CANDY, APPLE; see Fig. 5). Images initially appeared on the screen in silence for 2000 ms, before the onset of one of the two critical experimental sentences (e.g., *The monkey rides in the bus*). Each sentence consisted of the same form: article–agent–action–article–theme. As in Experiment 1, the duration and onset of each word within the sentences were aligned using Praat, such that the onset of each word in each sentence occurred at the same time across all sentences in the study. The alignment of word durations in each sentence allowed for a direct comparison of looking behavior with respect to the timing of the auditory stimulus across all experimental sentences. For each sentence (e.g., *The monkey rides the bus*), each image was classified in one of four conditions: target (BUS), agent-related (having been associated with the agent in the prior story, in the e.g., in Fig. 6, this was the CANDY), ACTION-RELATED (i.e., the other ride-able item, CAR), and unrelated (i.e., was not associated with the agent or the action of the sentence from the information presented in the novel story, in this case, APPLE). Although we developed the novel relations in this study to be infrequently encountered by young children, we also counterbalanced the stimuli to prevent the possibility that participants may have had some pre-existing

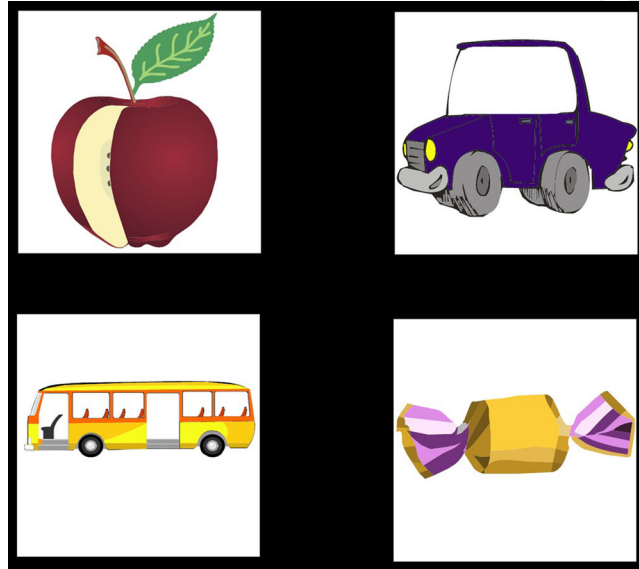


Fig 6. Illustration of images that appeared in the visual world sentence recognition task.

biases for some relationships over others. This counterbalancing scheme ensured that each image served in all target and distractor conditions across all versions of the study, yielding a balanced within-subjects design.

### 3.1.3. Procedure

**3.1.3.1. Experimental task:** As in Experiment 1, participants were seated in the same comfortable chair in the same experimental room equipped with an SR Eyelink 1000+ eye-tracker. The tracker was re-calibrated before starting Experiment 2. Participants were instructed that the task would be similar to the first, except that they would now hear stories about some creatures and that they should do their best to understand the story. Each child was told that after each story, they would hear additional sentences accompanied by four pictures and that they should point to the picture that “goes with the sentence.” Participants completed a single sentence comprehension practice trial before starting the experiment.

Each block in the study began with one of the four possible short story sets. Each story was narrated in a child-directed voice, and each “page” in the story was depicted on the computer screen as a colorful cartoon image that matched the spoken description. After each story, participants heard two sentences outlining one of the agent–action–object relationships from the previous narrative while they viewed items that varied in relation to the sentence-final target. Hence, participants completed eight trials in this sentence recognition task, and the entire task (including all story and sentence recognition phases) took less than 10 min to complete.

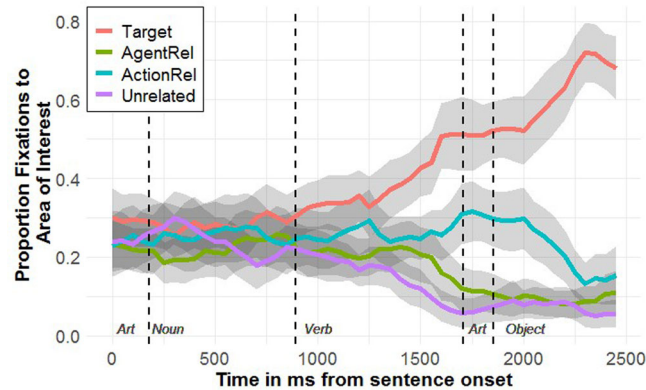


Fig 7. Time-course of fixations toward the target and competitor items from sentence onset to sentence offset. Note. Error cloud represents CIs. Dashed lines mark word onsets.

3.1.3.2. *Eye-movement recording:* Eye movements were recorded with the same equipment and parameters as in Experiment 1.

3.1.3.3. *Analytical approach:* As in Experiment 1, our analyses sought to establish whether and when participants fixated toward the target and competitor objects in relation to the spoken sentence. Our primary question concerned whether or not participants would make anticipatory eye movements toward the unspoken target of the sentence by utilizing the combinatorial relations or lexically associated relations from the prior story. Therefore, our analyses focused on the anticipatory time window comprising the onset of the spoken verb to the onset of the sentence-final noun. As in Experiment 1, analyses were carried out over broad and fine-grained time windows.

As in Experiment 1, we wished to verify that children were accurate and attentive in the analyzed trials. Therefore, we first removed trials in which children selected the incorrect target picture. This criterion led to the removal of 11 out of 272 total trials (4.0%), leaving 261 trials. As in Experiment 1, we next removed trials in which children did not view the target or distractor picture for more than 25% of the analyzed time window. This criterion led us to remove a further 23 trials (8.8% of remaining trials) from the broad time-window analysis, which was limited to the anticipatory time window, leaving a total of 238 total trials in this analysis. For the fine-grained cluster analysis involving the entire sentence time window, this criterion led to the removal of 8.0% of the remaining trials (21 out of 261, with 240 remaining).

### 3.2. Results

Fig. 7 highlights the time-course of fixations toward the target and three competitor images (agent-related, action-related, and unrelated) as the spoken sentence unfolds. As expected, fixations toward the target image increase dramatically after it is named in the spoken sentence. It is also visible that children fixated on the target item with a relatively greater magnitude

Table 4  
Regression model for Experiment 2

Effect/Slope	Estimate	CI	<i>t</i> -value	<i>p</i> -value
<b>(Intercept)</b>	<b>0.402</b>	<b>0.365–0.439</b>	<b>21.393</b>	<b>&lt;.001</b>
Area of Interest (Compared to Target)				
<b>Action-related</b>	<b>−0.139</b>	<b>−0.191–0.087</b>	<b>−5.235</b>	<b>&lt;.001</b>
<b>Agent-related</b>	<b>−0.213</b>	<b>−0.265–0.161</b>	<b>−8.009</b>	<b>&lt;.001</b>
<b>Unrelated</b>	<b>−0.257</b>	<b>−0.309–0.205</b>	<b>−9.658</b>	<b>&lt;.001</b>
Age	<0.001	−0.018–0.018	0	>.999
Trial index	<0.001	−0.018–0.018	0	>.999

Note. A version of this table for model outputs with random effects is available in the Supplementary Materials, Section 7.4.

than the other objects before the onset of the spoken object (i.e., predictively). These patterns are explored in the broad and fine-grained time-window analyses below.

### 3.2.1. Experimental effects on target fixations during a pre-determined anticipatory time window

To determine whether there was evidence for prediction of the target object, compared to other distractors, we first calculated the proportion fixations toward target and competitor objects during the anticipatory time window. Following prior work using similar paradigms, if looks toward the target exceed those to the other competitors during this anticipatory period (e.g., Borovsky et al., 2012; Kamide et al., 2003), then this is taken as strong evidence for anticipation of the target due to the multi-word information gleaned from the story (e.g., monkey–rides–bus). If, however, looks toward the target and action-related object (e.g., car) do not diverge before the sentence-final target is spoken, then this pattern is taken as support for the simple (pairwise) lexical-association account (reflecting the association between *ride* and ride-able objects, i.e., bus and car). We, therefore, entered the area of interest (AOI: target, agent-related, action-related and unrelated, with target as the reference level) into a linear mixed effects model along with age (in months, centered) and trial index (centered) with the lme4 library (Bates et al., 2015) in the R environment (R Core Team, 2016). The initial model included random effects for participants and items; specifically, we included by-item and by-subject random intercepts; however, this model experienced convergence issues due to little variance explained by the random effects. This model was compared to a model with no random effects and was not found to have any improvement in fit ( $LR = 5.6e-07$ ,  $p > .999$ ), so the final model reported here includes fixed effects only ( $Accuracy \sim AOI + Age + Trial\ Order$ ; see Table 4; the model summary for the (non-converging) model with random effects is reported is available in the Supplementary Materials, Section 7.4).

These analyses revealed no main effect of age or trial index (see Table 4 for beta coefficients for AOI levels and age and trial index). Follow-up pairwise tests of fixations toward the target, compared with other competitor objects, indicated that mean target fixation exceeded those to each of the other competitors during the anticipatory time window [target vs. action-related:  $t(920) = 5.24$ ,  $p < .0001$ ; target vs. agent-related,  $t(920) = 8.00$ ,  $p < .0001$ ; target

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Table 5

Significant differences between target and distractor objects identified by cluster-based permutation analyses

Comparison	Time window
Target versus action-related	1350–2500 ms (cluster $t = 108.54$ , $p < .0001$ )
Target versus agent-related	950–2500 ms (cluster $t = 200.07$ , $p < .0001$ )
Target versus unrelated	950–2500 ms (cluster $t = 235.51$ , $p < .0001$ )

*Note.* Timing is measured from the onset of the spoken sentence, which was 2455 ms in duration. The time-window where looking at the target significantly exceeded that to each of the distractors is reported in ms, followed by the cluster  $t$ -statistic and Monte Carlo  $p$ -value for that window, in parentheses. The onset of the sentence-final target was at 1854 ms post sentence onset. The reported  $p$ -values are Bonferroni-adjusted.

vs. unrelated:  $t(920) = 9.66$ ,  $p < .0001$ ]<sup>3</sup>. That is, children relied on multi-word information to generate predictions about the final object.

### 3.2.2. Finer-grained time-course analysis

As in Experiment 1, we used a cluster-based permutation approach to gain insight into the timing of the experimental effects. Again, we initially calculated a dependent measure of target-looking relative to that of each distractor item (agent-related, action-related, and unrelated). The results of these cluster analyses are outlined in Table 5; they clearly support the early broad window analysis that fixations toward the target diverged from those to each of the other competitors well in advance of the spoken *target* onset (which occurs at 1854 ms after sentence onset).

### 3.3. Discussion

Using a training paradigm, in which children were exposed to illustrated stories about animal characters engaged in unfamiliar actions, we sought to examine whether children form novel multi-word associations and whether they use them in predictive processing. Importantly, the frequency of multi-word combinations and individual lexical associations of the various agent–object and action–object pairwise combinations were fully controlled. If children simply generated predictions based on pairwise associations, rather than attending to higher-order multi-word information, then they would not have generated a specific prediction for one particular final object and instead would have shown equivalent fixations toward the target and action-related items (e.g., participants would have looked toward the BUS and CAR equally as they heard the verb “rides” in *The dog rides the bus*). Only if listeners rapidly attended to and interpreted information in the multi-word frame would they generate a specific prediction for a single sentence-final outcome that was more likely based on the story.

In line with our predictions, the results of this manipulation showed that children generated specific predictions for a single sentence-final outcome based on the multi-word contingencies in the story, rather than the pairwise lexical associations. Specifically, children’s fixations to the target exceeded those to all other distractors during the anticipatory time window. These results show that children were able to aggregate information about agents, actions,

and objects from the stories. Specifically, even though they never heard the sentence “The monkey rides in the bus” in this exact syntactic structure in the story, children were able to create the multi-word association between *monkey*, *ride*, and *bus* after hearing “Look! there’s a monkey! What’s that? He’s riding the bus! What’s he doing now? He’s eating the candy. What a silly monkey!” Creating such a multi-word association allowed them to predict BUS (and not CAR) long before it was produced, and shortly after hearing RIDE. These findings show that carefully controlling the frequency and content of multi-word information provides evidence for children’s use of multi-word information for predictive processing.

As we noted in our results’ section, age and trial did not contribute to this effect, suggesting that even the youngest children in our study (5 years old) were able to integrate multi-word information in real-time comprehension, and their ability to do so did not change (or adapt) over the course of the experiment. The lack of developmental change is consistent with a prior study that found that 5- to 10-year-olds could successfully use novel event knowledge to generate linguistic predictions (Borovsky et al., 2014), and with findings from the language production literature showing that even preschoolers may be sensitive to these multi-word effects (Arnon & Clark, 2011).

#### 4. General discussion

In the real world, children and adults integrate multiple words to successfully process sentences. Yet despite the growing evidence that multi-word sequences serve as building blocks in language learning and that they impact language processing (Arnon & Christiansen, 2017; Arnon & Cohen Priva, 2013; Arnon & Snider, 2010), the impact of multi-word sequences on generating predictions during real-time processing has been understudied. Specifically, while there is abundant evidence that both adults and young children rapidly generate real-time predictions about the form and meaning of upcoming speech, less work had explored whether and how children use multi-word information to generate predictions during online speech processing. Recent work on language production and comprehension suggests that adults and children are sensitive to multi-word contingencies above and beyond what can be simply explained by single word frequency effects (e.g., Arnon & Clark, 2011; Arnon & Snider, 2010; Bannard & Matthews, 2008), but it is not clear whether these findings would extend to real-time language comprehension. Therefore, the current project sought to explore whether multi-word frequencies impact real-time phrasal processing in young children. Our two experiments, using naturally occurring stimuli (Experiment 1) and newly constructed events (Experiment 2) provide the first thorough investigation of the effect of multi-word frequency on anticipatory and predictive processes. Importantly, our definition of multi-word sequences here refers to the associations between multiple words and their frequency; we do not refer to lexicalized wholes or abstract frames. Further, we do not dive into the question of whether children treat multi-word sequences as holistic wholes, and our work does not address the issue of when those processes occur in development (see recent evidence indicating that 12-month-old infants distinguish between high- and low-frequency trigrams, suggesting that they extract multi-word sequences from early on; Skarabela et al., 2021).

2 In Experiment 1, children did not seem to use the frequency of known multi-word  
3 sequences to generate real-time predictions. Here, 5- to 8-year-olds generated predictions  
4 toward target objects based on verb–object (*brush--hair*) associations rather than multi-word  
5 information (*Brush your hair*). Yet there were two main limitations to this particular design—  
6 the reliance on naturalistic variation in frequency, and the limited time to generate a predictive  
7 eye movement after the pronoun—that may have masked our ability to measure whether lis-  
8 teners were able to generate predictive eye movements toward the upcoming stimuli. The  
9 design of Experiment 2 allowed us to further unpack children’s ability to form predictions  
10 from multi-word sequences by examining their learning of novel multi-word sequences and  
11 better controlling the frequency of pairwise associations versus multi-word frequency. We  
12 used a learning paradigm that did not rely on naturalistic variation in multi-word frequency  
13 and that utilized a sentence structure that provided sufficient time for listeners to generate  
14 real-time predictions following a sentential verb. The findings in Experiment 2 indicated that  
15 multi-word frequency did impact language processing and that children used such informa-  
16 tion to form real-time predictions during language comprehension. Our results support an  
17 account of language processing where such multi-word information is learned and computed  
18 rapidly—at least when it has semantic content. Importantly, our results represent the first  
19 evidence that, at least in *some* circumstances, multi-word frequency can over-ride individual  
20 lexical associations and support real-time linguistic comprehension and prediction in chil-  
21 dren.

22 This finding raises intriguing questions regarding the relative impact of single-word and  
23 multi-word associations during online comprehension. Generating predictions from larger  
24 multi-word sequences may not always be optimal in cases where one word may provide  
25 greater informativity about the upcoming event than another (as in Experiment 1) or in cases  
26 where the linguistic message is highly uncertain. In particular, children may weigh multi-  
27 word and word information differently depending on many sources of information, including  
28 the strength of the pairwise and multi-word associations, event familiarity, speaker reliabil-  
29 ity, and semantic informativity. Such effects have been found in adult production, where,  
30 for example, the impact of trigram frequency on phonetic duration is stronger than that of  
31 word frequency for highly frequent sequences (Arnon & Cohen Priva, 2013). This contex-  
32 tual sensitivity may help explain why our first experiment, using brief utterances and more  
33 naturalistic stimuli, found only moderate support for the impact of multi-word information  
34 on language comprehension. In the case of the stimuli in Experiment 1, listeners seemed to  
35 primarily rely on the most semantically informative unit, the verb, to guide predictions rather  
36 than on the less salient and informative function word (preposition/article/pronoun). How-  
37 ever, in our constructed sentences in Experiment 2, these very same participants showed a  
38 different pattern of behavior: When each word in the multi-word sequence contributed clear  
39 semantic information (e.g., *monkey, ride, bus*), this manipulation led to a greater reliance on  
40 the multi-word sequence (relative to the verb–object associations) to form predictions. Our  
41 results also support the idea that proficient language users, including young children, can  
42 dynamically shift their strategies for linguistic prediction based on the information available  
43 in the linguistic task at that moment. This pattern is most consistent with recent proposals  
44 that highlight adaptive processes in language comprehension as listeners flexibly shift their

1  
2 strategies to make optimal use of available information, such as that put forward in the “utility  
3 account” proposed by Kuperberg and Jaeger (2016).

4 Next, we note some limitations of the current work. First, as mentioned earlier, our experi-  
5 mental participants were school-age children, between the ages of 5 to 8 years. While impor-  
6 tant developmental changes in school-aged children occur in a number of linguistic processing  
7 abilities ranging from phonemic category distinction (Hazan & Barrett, 2000) to the integra-  
8 tion of referential cues to meaning in sentences (Snedeker & Trueswell, 2004; see Creel &  
9 Quam, 2015, for a review), this age group did not demonstrate strong evidence of develop-  
10 mental change in processing in either experiment. It should be noted that our testing of 5- to  
11 8-year-old children was directly motivated by prior studies that found that school-age chil-  
12 dren (5- to 10-year-olds), but not preschoolers (3- to 4-year-olds), could successfully use a  
13 novel event to generate real-time predictions in a similar task (Borovsky et al., 2014). Future  
14 work is therefore needed to determine whether these patterns would also extend to younger  
15 children and whether younger children would modify their ability to integrate multi-word  
16 information in sentence comprehension. However, the complexity of the current task may  
17 require significant modifications before it can be implemented with younger children.

18 Second, given that children’s linguistic experiences reflect their real-world knowledge and  
19 lived experiences of events, it is necessary to consider that novel events in Experiment 2 cap-  
20 italized on the listeners’ pre-existing verb/action knowledge, where novel agents interacted  
21 with various objects using actions that were semantically licensed by particular verbs. Thus,  
22 not all elements of these “novel” events were truly novel, and our results, like many from sim-  
23 ilar experimental tasks, are not free from “contamination” from real-world knowledge. One  
24 concern about relying on these pre-existing verb–object associations is that children may have  
25 used these pairwise associations to drive behavior in Experiment 2. While this is certainly a  
26 possibility, our counterbalancing scheme ensured that all verbs were paired with all objects  
27 across all versions of the study. Therefore, if some verb–object associations were stronger  
28 than others (i.e., *ride–car* may be more frequent/strongly associated than *ride–bus*), these  
29 associations would have been balanced out in our design. While an even stronger test of our  
30 hypotheses would have been to generate a design where all relations were completely novel  
31 (with novel agents, actions, and objects), it is likely that this design would have been challeng-  
32 ing for children. Indeed, an experiment where adults learned novel combinatorial relations in  
33 an artificial language among novel agents, actions, and objects, required extensive repetition  
34 and training (Amato & MacDonald, 2010). To gain a fuller picture of how children learn about  
35 complex relations among words and events, much more work is needed, potentially using nat-  
36 uralistic (albeit complex) paradigms where learning is measured over multiple contexts over  
37 several days.

38 Third, in interpreting our results, we must acknowledge the possibility that children may  
39 have relied on visual priming from the pictures for predictive processing. The design of both  
40 our experiments does not allow us to ascertain the extent to which the visual context and  
41 linguistic cues have individually facilitated processing or whether they worked in concert;  
42 hence, we do not think we can make any inferences about children’s reliance, or lack thereof,  
43 on referential context. This issue has been directly investigated in several sentences processing  
44 studies with unclear results as to the extent to which children rely on referential context.

2 For instance, some studies showed that referential processing may be harder for younger  
3 children (e.g., Kidd & Bavin, 2005; Rabagliati & Robertson, 2017; Snedeker & Trueswell,  
4 2004), while others provide evidence that children can use referential contexts for generating  
5 accurate predictions (e.g., Huang & Snedeker, 2008; Reuter, Dalawella, & Lew-Williams,  
6 2021). Only more work carefully controlling for the effects of pairwise associations, multi-  
7 word sequences, as well as referential context can help address this issue in more detail.

8 Despite these limitations, our research provides initial support for the idea that children  
9 are sensitive to multi-word information in predictive language processing, at least in cases  
10 where the sequences contain multiple semantically informative units as in Experiment 2. A  
11 clear and necessary path forward for future work would be to parametrically manipulate the  
12 potential utility of various multi-word sequences in predictive processing paradigms, perhaps  
13 by using a training paradigm that manipulates the local frequency of experimental test sen-  
14 tences that conform to prior multi-word associations across the course of a study. Further, it  
15 will be interesting to explore how different frequency and probability measures may impact  
16 and contribute to predictive processing. Specifically, instead of defining multi-word associa-  
17 tions by their frequency in the input, it is possible to define them in terms of the conditional  
18 probabilities between the different elements (e.g., McCauley & Christiansen, 2019). As such,  
19 it will be intriguing to explore whether defining multi-word sequences in this manner pro-  
20 vides a more sensitive measure of their impact on predictive processing. Moreover, individual  
21 differences are also likely to contribute to performance on these multi-word processing tasks,  
22 just as they do in other sentence processing tasks (Borovsky & Creel, 2014; Borovsky et al.,  
23 2012; Kukona et al., 2016; Mani & Huettig, 2012). Some potential candidates for skills that  
24 could contribute to multi-word sequence comprehension include working memory (Huettig &  
25 Janse, 2016), statistical learning skills (Misyak, Christiansen, & Tomblin, 2010), and cogni-  
26 tive flexibility/inhibitory control (Woodard, Pozzan, & Trueswell, 2016). It is likely that these  
27 same kinds of skills contribute to learning about multi-word sequences in natural language  
28 processing. Future work is necessary to explore precisely how and when in development vari-  
29 ous cognitive skills may interact with processing multi-word chunks in sentences.

30 In sum, this project has demonstrated that young children can rapidly generate predictions  
31 during language processing based on higher-order multi-word chunks in sentences, although  
32 this process is (at least) limited to conditions where there are multiple semantically infor-  
33 mative units in the linguistic stream. Our findings lend support to recent accounts of flexible  
34 linguistic processing and suggest that even very young, school-age children are highly sophis-  
35 ticated in their ability to rapidly compute and generate predictions for higher-order relations  
36 among multi-word sequences during linguistic comprehension.

### 37 Notes

- 38
- 39
- 40 1 One experimental item, “Drink of water” did not contain a verb (see Appendix A). Fol-  
41 lowing the recommendation of an anonymous reviewer, we re-ran our analyses after  
42 removing all “drink” trials. The statistical patterns remained the same, with the excep-  
43 tion of the *Trial Order* effect that became no longer significant ( $p = .102$ ). Importantly,  
44 the main effect of *Frame Frequency* remained significant even after removing these

1 trials. The statistical output of these analyses is provided in Table 1 in the Supplementary  
2 Materials, Section 7.3.

3 2 We thank an anonymous reviewer for suggesting this possible interpretation of our find-  
4 ings.

5 3 These statistical patterns were identical when carrying out the same analyses using an  
6 empirical-logit transformation of the data.  
7  
8

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11  
12

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14 The authors have no conflicts to disclose.  
15  
16

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22 **Supporting Information**

23 Additional supporting information may be found  
 24 online in the Supporting Information section at the end  
 25 of the article.

26  
 27 **Fig. S1.** Time-course of proportion fixations to target  
 28 and distractor images for high- (frequent and modified)  
 29 and low-frequency (frequent and modified) frames.

30 **Table S1.** Linear mixed effects regression model for  
 31 Experiment 1 after removing all “drink” trials

32  
 33  
 34 **Appendix A: List of all sentences and their frequency information for all conditions in**  
 35 **Experiment 1**

36 Condition	37 Frame Frequency	38 Object Frequency	39 Verb–Object Frequency
40 <b>FF-High</b>			
41 Brush your teeth	18.50	236.83	36.50
42 Close your eyes	19.00	293.50	26.17
43 Drink of water	10.83	950.33	21.50

44 (Continued)

Condition	Frame Frequency	Object Frequency	Verb–Object Frequency
Open the door	42.17	429.83	50.83
Throw the ball	21.50	809.00	24.33
Want your bottle	6.17	226.33	12.83
Wash your hands	41.33	390.17	66.83
<b>FF-Low</b>			
Brush your hair	5.50	491.67	24.33
Close your mouth	2.17	461.67	2.83
Drink of milk	4.50	581.67	19.67
Open the window	1.17	164.50	4.33
Throw the book	0.50	1285.67	1.50
Want your book	2.17	1285.67	20.17
Wash your hair	5.50	491.67	11.50
<b>MF-High</b>			
Brush her teeth	0.50	236.83	36.50
Close his eyes	0.17	293.50	26.17
Drink some water	2.50	950.33	21.50
Open a door	0.83	429.83	50.83
Throw your ball	0.17	809.00	24.33
Want a bottle	3.00	226.33	12.83
Wash her hands	2.00	390.17	66.83
<b>MF-Low</b>			
Brush her hair	0.50	491.67	24.33
Close his mouth	0.50	461.67	2.83
Drink some milk	3.00	581.67	19.67
Open a window	0.83	164.50	4.33
Throw your book	0.17	1285.67	1.50
Want a book	3.33	1285.67	20.17
Wash her hair	2.00	491.67	11.50

*Note.* These numbers represent the frequency of each item per 1 million words calculated from a corpus of ~6 million words.

Abbreviations: FF-High, familiar frame–high frequency; FF-Low, familiar frame–low frequency; MF-High, modified frame–high frequency; MF-Low, modified frame–low frequency.

## Appendix B: Outline of the agent, action, and thematic object sets used in Experiment 2

Set	Agents	Action1	Object 1	Action2	Object 2
<b>Set 1</b>	Monkey, dog	Eats	Candy, apple	Rides in	Car, bus
<b>Set 2</b>	Mouse, cat	Tastes	Ice cream, cake	Wears	Hat, glasses
<b>Set 3</b>	Turtle, frog	Turns on	TV, computer	Cuts	Paper, bread
<b>Set 4</b>	Lion, duck	Flies	Kite, airplane	Sits on	Rock, fence

*Note.* In each story set, each agent performed both actions, and different agents were associated with different objects (e.g., if the monkey eats the candy, then the dog eats the apple). In each set, each verb was additionally paired with one of the potential two objects in a frame that did not mention either of the agents (e.g., Let's eat the apple). All possible combinations of agents, actions, and objects occurred across lists in the study.