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Predictable Events Enhance Word Learning in Toddlers

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SUMMARY

Sensitivity to the predictability of the environment supports young children's learning in many domains [1, 2], including language [3–6]; perception [7, 8]; and the processing of objects, space, and time [1, 9]. Predictable regularities allow observers to generate expectations about upcoming events and to learn from violations of those expectations [10, 11]. Given the benefits of detecting both predictable and unpredictable events, a key question concerns which types of input facilitate learning in young children. In the current research, we assessed the effects of predictability on toddlers' word learning by embedding word-learning moments within events that were either predicted or violated predictions. 2-year-olds observed a continuous visual sequence in which novel objects were revealed from one of four locations in a predictable spatiotemporal pattern (1, 2, 3, 4). Objects were then labeled either during events that were predicted by the sequence (1, 2, 3, 4) or events that violated the sequence (1, 2, 3, 2). Results from two studies revealed better word learning for objects labeled during predictable events than objects labeled during unpredictable events. These findings suggest that predictable events create advantageous learning moments for toddlers, with implications for the role played by predictable input in early development.

In Brief

Benitez and Saffran examined whether predictability affects children's word learning. Toddlers viewed objects labeled during predictable or unpredictable events in a sequence. Label-object pairs were learned better when they were presented during predictable events, suggesting that predictable events create advantageous learning moments for toddlers.

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AUTHOR CONTRIBUTIONS

V.L.B. and J.R.S. designed the experiments, V.L.B. conducted the experiments and the analyses, and V.L.B. and J.R.S. wrote the paper.

SUPPLEMENTAL INFORMATION

Supplemental Information includes two videos and can be found with this article online at <https://doi.org/10.1016/j.cub.2018.06.017>.

DECLARATION OF INTERESTS

The authors declare no competing interests.

RESULTS

We presented toddlers ($n = 107$, see Experimental Model and Subject Details) with novel information to be learned (label-object pairings; Figure 1A) embedded within a predictable sequence of visual events (Figure 1B). Participants first observed the sequence of events: boxes opened and closed in a consistent, spatiotemporal pattern (1, 2, 3, 4), revealing images of objects one at a time (sequence-exposure phase; Figure 1B). What was predictable was when and where an object would be revealed, but never which object would be revealed. No labeling occurred during this phase.

After five repetitions of the spatiotemporal event sequence, labeling moments were embedded within the sequence (sequence-labeling phase; Figure 1B). Half of the objects were labeled during predictable events: the expected box opened according to the sequence to reveal the object that was about to be labeled (1, 2, 3, 4). The other half of the objects were labeled during unpredictable events: the spatiotemporal sequence was violated such that an unexpected box opened to reveal the object about to be labeled (1, 2, 3, 2; Videos S1 and S2). To avoid confounds related to the effects of predictability on visual attention, we used a gaze-contingent eyetracking paradigm; objects were not labeled until the child looked at them. Thus, regardless of their expectations, toddlers only heard the name of an object after they fixated on it. We then tested word learning using the looking-while-listening procedure [12] (testing phase; Figure 1C).

The key question was whether toddlers showed differential retention of label-object pairs presented during predictable events relative to label-object pairs presented during unpredictable events. If predictable events benefit learning, then label-object pairs embedded in predictable events should be learned better than label-object pairs embedded in unpredictable events. If, on the other hand, unpredictability facilitates learning, then children should learn the label-object pairs better for objects labeled during unpredictable events than predictable events. In experiment 1, we tested 50 toddlers (26–29 months of age). Experiment 2 was an exact replication of experiment 1 other than a shortened test phase and included 57 toddlers.

Did Children Track the Spatiotemporal Pattern?

We first assessed whether children learned the spatiotemporal pattern based on their looking behavior on trials in which objects were about to be labeled (labeling moments). There were three labeling moments for each of four objects (six during predictable events and six during unpredictable events). To assess pattern learning, we measured the latency to orient to the box before labeling occurred. The critical time window was from the start of the interstimulus interval (ISI) to the moment when the label was triggered by the child's look (Figure 1B). We excluded trials that timed out (no look was detected within the 5-s window, and the label was presented automatically).

In experiment 1, toddlers timed out on 2.96 trials (12 possible). The average number of time-out trials was similar for predictable events (mean = 1.66, SD = 1.81) and unpredictable events (mean = 1.3, SD = 1.64; $F(1,49) = 2.75$, $p = 0.10$). We considered looks longer than 2 SDs above the mean to be due to inattentiveness or a poor track; these slow reaction times

(RTs) were excluded (5.06% of the dataset). RTs to objects revealed during unpredictable events were slower (mean = 1379 ms, SD = 231 ms) than RTs to objects revealed during predictable events (mean = 1282 ms, SD = 364 ms; $F(1, 198.21) = 5.94$, $p = 0.02$; Figure 2A). Neither the effect of naming instance ($F(2, 198.84) = 1.07$, $p = 0.34$) nor the interaction between naming instance and event type ($F(2,200.73) = 0.93$, $p = 0.39$) were significant.

In experiment 2, we replicated these effects (Figure 2B). Toddlers timed out on 3.79 trials (12 possible). The number of time-out trials was the same for predictable events (mean = 1.89, SD = 1.83) and unpredictable events (mean = 1.89, SD = 1.71). We again excluded looks longer than 2 SDs above the mean (5.21% of the dataset). RTs to objects revealed during unpredictable events were slower (mean = 1437, SD = 261) than RTs to objects revealed during predictable events (mean = 1307, SD = 383; $F(1,220.15) = 6.3$, $p = 0.01$). Neither the effect of naming instance ($F(2,224.79) = 0.08$, $p = 0.93$) nor the interaction between naming instance and event type ($F(2,224.57) = 1.68$, $p = 0.19$) were significant. The RT results of both experiments 1 and 2 indicate that toddlers formed expectations about which box would open up next and successfully tracked the spatiotemporal sequence within which the naming events were embedded.

Anticipatory Looks—As a second measure of sequence learning, we measured anticipatory looks during the ISI for trials in which an object was about to be labeled (Figure 1B). Consistent with the claim that children tracked the spatiotemporal pattern, participants were more accurate in anticipating which box would open up before a labeling moment occurred for predictable events than for unpredictable events in both experiments (see Quantification and Statistical Analysis).

Proportion Looking Time—To ensure children had an equal opportunity to learn all object-label pairs, we assessed overall looking time to the objects during the two types of labeling events. The time window for this analysis was from the moment the box cover began lifting through when the object was labeled and until the box cover closed (Figure 1B). All trials were included.

In experiment 1, there was no significant difference in proportion looking time to objects presented during predictable events (mean = 0.84, SD = 0.14) versus unpredictable events (mean = 0.82, SD = 0.13; $F(1,245) = 2.83$, $p = 0.09$; Figure 3). There was a significant effect of naming instance ($F(2,245) = 5.09$, $p = 0.007$) and a significant interaction between event type and naming instance ($F(2,245) = 3.03$, $p = 0.05$). Follow up analyses revealed no significant comparisons.

Similarly, in experiment 2, there were no differences between predictable events (mean = 0.85, SD = 0.15) and unpredictable events (mean = 0.80, SD = 0.19; $F(1, 276.49) = 1.86$, $p = 0.17$) or between naming instances ($F(2,276.34) = 1.32$, $p = 0.27$). The interaction was not significant ($F(2,276.65) = 0.03$, $p = 0.97$). Together, these findings show that children's proportion looking time during the labeling moments was similar for predictable and unpredictable events.

Does Predictability Affect Word Learning?

Our primary question was whether predictability within the spatiotemporal sequence during labeling affected word learning. Objects were yoked such that each test trial contained either a pair of objects presented during predictable events or a pair of objects presented during unpredictable events. In experiment 1, there were 16 test trials grouped into two blocks of 8 trials each (2 tests per object in each block). A large proportion of looking data from the test phase was not recorded by the eye tracker. The proportion of missing data was greater for block 2 (53.6%) than for block 1 (35.2%), suggesting increased inattentiveness and poor tracks toward the end of the test phase. The first analysis for experiment 1 included both blocks of test trials, and the second analysis included only block 1. In experiment 2, the test phase was shortened to include only eight test trials (two tests per object).

Experiment 1: All Test Trials—Of the 50 toddlers that were tested, 20 toddlers were excluded for having less than 50% recorded looking data during the test phase. Consistent with previous studies, the critical time window began 300 ms after word onset (to account for planning an eye movement) and lasted 3,000 ms. Trials on which children were not looking at either of the two pictures at the onset of the word were excluded (24.2% of the dataset) [12–16]. In experiment 1, each child contributed an average of just under six test trials for each condition out of a possible eight (predictable: mean = 5.8, SD = 1.5; unpredictable: mean = 5.9, SD = 1.6). During the critical time window, we calculated accuracy by dividing the total amount of looking time to the correct object by the total amount of looking time to either object.

Toddlers performed significantly better than chance when tested on objects labeled during predictable events (mean = 0.58, SD = 0.15; $F(1, 29) = 8.13$, $p = 0.008$), but not objects labeled during unpredictable events (mean = 0.55, SD = 0.17; $F(1, 29) = 3.06$, $p = 0.09$). There was no significant difference in accuracy for label-object pairings presented during predictable versus unpredictable events ($F(1,29) = 0.56$, $p = 0.46$; Figure 4A).

Experiment 1: Block 1 Test Trials—This analysis only included block 1 (eight test trials, each object tested twice). Five toddlers excluded from the previous analysis were included ($n = 35$); 15 toddlers remained excluded for having less than 50% recorded looking behavior for block 1. We set our critical window, excluded trials (16.3% of total data), and calculated proportion looking times as in the previous analysis. Toddlers contributed on average just over three test trials per condition out of a possible four (predictable: mean = 3.29, SD = 0.86; unpredictable: mean = 3.2, SD = 0.87).

The results for block 1 alone (Figure 4B) showed that toddlers successfully learned the label-object pairs presented during predictable events (mean = 0.61, SD = 0.19; $F(1,34) = 11.86$, $p = 0.002$) but were unsuccessful at learning the label-object pairs presented during unpredictable events (mean = 0.54, SD = 0.21; $F(1,34) = 1.16$, $p = 0.29$). In contrast to the analysis of the full dataset from experiment 1, the analysis of block 1 test trials revealed that toddlers were significantly more accurate for label-object pairs presented during predictable events than unpredictable events ($F(1,34) = 4.25$, $p = 0.047$).

Experiment 2: Shortened Test Phase—Given the high rate of data loss in the second test block of experiment 1, experiment 2 was designed as an exact replication with only eight test trials (two tests per object). We again only included toddlers that contributed looking data for at least 50% of the test phase (excluding 21 toddlers, $n = 36$) and excluded trials in which toddlers were not looking at either of the two pictures at word onset (19.4% of the dataset). On average, each child contributed just over three of a possible four test trials for each condition in experiment 2 (predictable: mean = 3.17, SD = 0.97; unpredictable: mean = 3.17, SD = 0.91).

Toddlers performed significantly better than chance when tested on label-object pairs trained during predictable events (mean = 0.69, SD = 0.13; $F(1, 35) = 71.18$, $p < 0.001$), but not unpredictable events (mean = 0.56, SD = 0.21; $F(1,35) = 2.9$, $p = 0.10$; Figure 4C). There was a significant difference between the two conditions: toddlers learned words better for objects trained during predictable events than during unpredictable events ($F(1,35) = 11.11$, $p = 0.002$).

Finally, we combined the test data for experiment 1 (block 1) and experiment 2 (see Quantification and Statistical Analysis). The results again showed an accuracy advantage for objects labeled during predictable events over objects labeled during unpredictable events, even when accounting for experiment, vocabulary, age, or gender.

DISCUSSION

Predictive processes play an important role in learning in many domains [1, 3, 4, 7], and recent proposals link disrupted predictive processes to developmental disabilities [17, 18]. Given the importance of predictive processes for developmental outcomes, it is important to understand how predictability affects learning. Our results revealed that when word-learning moments were embedded within predictable events, toddlers showed more accurate test performance than when word-learning moments were embedded within events that violated predictions. This effect was observed despite the fact that predictability was unrelated to the objects themselves (the manipulation concerned the events within which labeling moments were embedded), and children had equal learning opportunities to acquire all label-object pairs.

What are the mechanisms that might lead to facilitation of learning from predictable events? One mechanism proposed by models of learning and behavioral data in adults concerns attentional processes [10,19–23]. There are several, non-mutually exclusive ways that attention may play a role in mediating the effect of predictability on learning. The first is through an attentional preference for predictable input. Adult studies suggest enhanced attention to sequences of events that are highly predictable [10, 19–23]. If predictable events promote sustained attention, then it is also possible that the unpredictable events disrupted attention (by disrupting the sequence), leading to weaker encoding of information. This idea is consistent with findings suggesting that adults remember visual stimuli more poorly when they violate a predictable sequence [24].

A second way that attention may have yielded learning benefits from predictable events is through prediction. The process of generating predictions about upcoming information may activate that information in memory, which gets reinforced when the event actually occurs [24]. Additionally, being able to predict where and when something will happen next might allow young children to get to the information faster, generating better processing of rapidly incoming input [25].

Toddlers' looking behavior in our task provides a proxy for attention and insight into the attentional mechanism(s) that might be at play. Overall looking times to objects to be labeled were the same for predictable and unpredictable events. However, children oriented more quickly to the box that was about to reveal the object that was to be named, perhaps allowing them to more easily process the novel label and map that label to the object when it was revealed [26]. Being able to predict what happens next might be particularly beneficial for learning in tasks with temporal dimensions, such as those involving sequential processing. However, we did not find that the degree of expectations during the sequence of events predicted an accuracy advantage for predictable events at test (see Quantification and Statistical Analysis). Future research will have to employ additional measures of attention to more directly assess how attention plays a role in the learning advantage for predictable events.

Our findings appear to be inconsistent with recent research demonstrating that violations of expectations support novel learning in infants and children [27, 28] and with proposals suggesting that violations of expectations play an important role in acquiring novel regularities [11, 29–33]. One possibility for this inconsistency is that predictability and violations of predictions may have different effects on learning because they elicit different responses. If novel information is presented shortly after a predictable event, as in the current study, learning may benefit because the predictable events cause an immediate response that heightens attention [8]. The benefits of learning from violations of expectations may not be seen until later, when the system has taken time to interpret the event as a prediction error, signaling the need to further explore the unexpected situation [8, 27, 28]. Another important factor to consider is the manner in which predictability is manipulated. In the current studies, predictability was not an aspect of the objects themselves but was instead reflected in the sequence within which label-object pairs occurred. In studies in which predictability was implemented via violations of expectations, the objects themselves behaved in highly unexpected ways (e.g., hanging in the air, traveling through barriers [27, 28]). Both the nature of the violations (event sequences within which objects are embedded versus the objects' properties themselves) and the severity of the violations (disruption of a recently learned sequence versus core knowledge) may impact the directionality of the effect. A more complete understanding of predictive processes and their effects on learning will require an integrated account of young children's responses to both expectations and violations of expectations [30, 33–42].

Our findings are consistent with recent results demonstrating that consistency during naming events promotes word learning [26] and with models of learning and adult behavioral data that show an advantage for attention, memory, and learning of stimuli presented within predictable sequences [10, 19–24, 35, 42]. These findings suggest that predictability can be

beneficial across the developmental spectrum. However, predictability might be particularly critical for young children. Because their memory representations are fragile [43–45], consistency might be particularly helpful in building memory representations that can be carried from one learning moment to the next. Moreover, previous research suggests a positive link between developmental outcomes and the ability to make predictions [17, 18, 41], as well as the amount of predictability and stability present in young children’s home environments [46–49]. Our results suggest that these links may be due, in part, to the benefits of the predictability of input for learning.

In conclusion, the studies presented here provide evidence for the importance of predictable input for novel word learning. Young children’s learning benefits when novel information is embedded within predictable sequences. Predictable events can create advantageous learning moments for toddlers and are key to learning new information from structured input.

STAR ★ METHODS

CONTACT FOR REAGENT AND RESOURCE SHARING

Further information and requests for resources and reagents should be directed to and will be fulfilled by the Lead Contact, Viridiana L. Benitez (viridiana.benitez@asu.edu).

EXPERIMENTAL MODEL AND SUBJECT DETAILS

Experiment 1—Fifty 26- to 29-month-olds (30 females; $M = 27.14$ months, $SD = 0.71$) were included in the sample. An additional 11 toddlers were tested but excluded due to fussiness. Toddlers were English-learning and full term with no known vision or hearing problems and no exposure to a second language. Families were recruited from the Madison, WI community and received a gift for participating in the study.

Experiment 2—Fifty-seven 26- to 29-month-olds (27 females; $M = 27.36$, $SD = 0.67$) were included in the sample. Demographics and exclusion criteria were identical to Experiment 1. An additional 14 toddlers were tested but excluded because of fussiness (12) or a failure to calibrate (2).

The University of Wisconsin – Madison Institutional Review Board approved the study and parental consent was obtained for all children tested in Experiment 1 and 2.

METHOD DETAILS

Stimuli

Novel stimuli: The label-object pairings consisted of 4 images and 4 novel words from the Novel Object and Unusual Name Database (Figure 1A) [50]. Each object was selected to be distinct and interesting for young children. Objects were presented against a white background. Words and objects were randomly paired to create four label-object pairings. We divided the pairings into two sets of two label-object pairings. Each set was composed of a monosyllabic and a bisyllabic word. Assignment of sets to Predictable versus Unpredictable Events was counterbalanced across participants.

Auditory stimuli were produced by a female native English speaker in child-directed speech. Words were recorded in isolation, normalized for intensity and duration, and presented in carrier phrases (e.g., “It’s a sarn!”) normalized for intensity.

Familiar stimuli: We selected 16 images of objects familiar to this age group (e.g., airplane, cat, bear). Two objects appeared during the Sequence Exposure Phase, and 12 appeared during the Sequence Labeling Phase. During both phases, familiar objects were intermixed with the novel objects in order to maintain toddlers’ attention. The final two familiar objects were presented during the test to familiarize toddlers with the test procedure. The familiar labels and objects were subject to the same recording and processing procedures as the novel items.

Design—The training procedure was divided into two phases, followed by testing. In the Sequence Exposure Phase, toddlers were exposed to a spatiotemporal pattern without labels. In the Sequence Labeling Phase, toddlers continued to view the same spatiotemporal pattern, with the novel objects labeled throughout.

During both training phases, all images were presented at one of 4 locations (arranged in a square) on a black screen (Figure 1B). Each location contained a blue box with a red border. The front “cover” of the box (the blue portion) lifted and closed to reveal an image of an object on a white background hidden behind the cover of the box. The timing of opening and closing of the boxes was as follows: a 700 ms ISI (the time between when one box closed and the next box opened), 500 ms to lift the box cover, 500 ms with the object fully in view, and 500 ms for the cover to close. We defined all events as the moment when the ISI began, through when a box opened and revealed an object, until it closed. Only a single box was ever open at any time.

Critical to the design was the spatiotemporal pattern in which the events occurred: boxes opened and closed to reveal objects in a sequence, beginning with the top left box, and moving clockwise to end with the bottom left box (sequence: 1, 2, 3, 4; each number corresponds to the location that reveals an object: 1- top left box, 2 – top right box, 3 – bottom right box, 4 – bottom left box). The object presented when each box opened was randomized across events, so that all objects could appear in any of the boxes (except for labeling moments, see below).

Sequence Exposure Training Phase: During the Sequence Exposure phase, toddlers observed 5 repetitions of the full spatiotemporal pattern (1, 2, 3, 4; see Figure 1B). The 4 novel objects were randomly presented at all of the different locations, with the constraint that the same object was never presented twice in a row. Toddlers saw each novel object 4 times, randomly intermixed with the presentation of two familiar objects, each presented twice. A child-friendly piano song was played in the background during this phase to increase interest in the video. No labeling occurred during this phase. The Sequence Exposure Phase lasted 1.5 min.

Sequence Labeling Training Phase: During this phase, objects continued to be revealed according to the spatiotemporal sequence, except for specific moments in which the novel

objects were labeled (see Figure 1B). During these labeling moments, we manipulated whether the object was presented at a Predictable Event in the sequence (an event that was consistent with the spatiotemporal sequence; 1, 2, 3, **4**), or an Unpredictable event in the sequence (an event that violated the spatiotemporal sequence; 1, 2, 3, **2**). Two objects were always labeled during Predictable Events, and the other two were always labeled during Unpredictable Events. Label-object pair assignment to Predictable versus Unpredictable Events was counterbalanced across participants.

At each labeling moment, a novel object was revealed as usual (see Figure 1B). The label was presented in a carrier phrase when the object was fully in view and the child looked at the object (see Videos S1 and S2). That is, labeling was gaze-contingent: after the eye-tracker coded 70 ms of continuous looking to the object that was revealed (beginning from the moment that the box cover lift was completed), the labeling phrase was presented. This ensured that regardless of children's expectations, labels were only presented when a child was fixating the object. If the eye-tracker did not code a 70 ms continuous look by the child within a 5 s wait period, the label was presented automatically (the proportion of trials that resulted in the label being presented automatically was equal across Predictable and Unpredictable Events, see Results).

Each novel object was labeled 3 times within the sequence. Predictable and Unpredictable Events were interspersed during the Sequence Labeling Phase according to two pre-specified orders, counterbalanced across children. For Predictable Events, each labeling moment occurred embedded within one full sequence repetition (i.e., there could never be a second labeling moment before all events in the sequence occurred). For Unpredictable Events, the sequence continued correctly after the labeling moment - the box that opened up after an Unpredictable Event was always the box that correctly followed the spatiotemporal sequence (e.g., 1, 2, 3, **2**, 3, 4). After an Unpredictable Event, the full correct sequence was repeated once without a labeling moment before the next labeling moment occurred. In order to minimize interference from seeing different objects labeled at the same location [26], each object was always labeled at a specific and unique location (e.g., Child 1 saw Object 1 labeled during a Predictable Event at Location 1 for all three naming instances, Child 2 saw Object 1 labeled during an Unpredictable Event at Location 2 for all three naming instances).

During the events that did not include labeling, toddlers saw a mixture of the novel objects and the 12 familiar objects not used during Sequence Exposure Phase. Each novel object occurred 9 additional times without being labeled, and familiar objects each occurred twice. The objects were intermixed with the constraint that the same object could not appear twice in a row, and, except for labeling moments, could appear at any location. The entire Sequence Labeling Phase lasted approximately 3 min.

Testing: Children were tested using a looking-while-listening procedure [12]. On each trial, two objects were displayed on the screen, and the target object was labeled in a carrier phrase, with the label in the final position. Then an attention getter phrase followed (e.g., "Where's the sarn? That's cool!"; see Figure 1C). The timing of all phrases and words were

controlled so that the label started and ended at the same time point for all test trials. Each test trial lasted 6 s.

Children were first presented with two familiar test trials (a ball and a shoe) to familiarize them with the test procedure. They then received either 16 test trials (Experiment 1) or 8 test trials (Experiment 2) testing the word-object pairings presented during the Sequence Labeling Phase. Objects were yoked such that the two objects presented during Predictable Events were always paired and the two objects presented during Unpredictable Events were always paired. In Experiment 1, test trials were grouped into two blocks of 8 test trials each. During each block, each object served as the target twice and the distractor twice, with the location of the target counterbalanced across trials, and test trials pseudo-randomized within a block. Two test orders were created and counterbalanced across children. Attention getters (a scene of a beach, air balloons, or ocean life, paired with a motivating phrase, e.g., “You’re doing great!”) were presented at the beginning of the test phase and after every 6 test trials. Testing lasted approximately 2 min. In Experiment 2, each object was tested on two trials for a total of 8 test trials. Location of the target object was counterbalanced, and order of the test trials was pseudo-randomized to create two test orders, counterbalanced across participants. Attention getters were presented every 3 test trials; testing lasted approximately 1.5 min.

Procedure—Toddlers sat on their caregiver’s lap in a sound attenuated booth in front of a Tobii Pro T60XL monitor and eye-tracker. The eye-tracker was calibrated to each child’s eye-movements using the 5-point Tobii Studio calibration procedure. After calibration was completed, infants were presented first with the Sequence Exposure Phase, then the Sequence Labeling Phase, and finally the Test Phase of the experiment, all in a continuous video. Caregivers wore dark glasses so they could not see the video. The video lasted approximately 6.5 min. Parents were asked to fill out an electronic version of the MacArthur Bates Communicative Development Inventory, Words and Sentences Short form (MBCDI) after the study [51].

QUANTIFICATION AND STATISTICAL ANALYSIS

For all analyses examining effects of condition (Predictable versus Unpredictable), we assessed toddlers’ mean responses by estimating linear mixed effects models (fit using Maximum Likelihood Estimation) and comparing these models using the Kenward-Roger approximation method to estimate degrees of freedom [52] using R (version 3.4.3), package lme4 (version 1.1-15) [53]. Each model included the relevant fixed effects as specified and a random intercept for subject. For analyses comparing toddler’s test performance to chance, we calculated linear regression models on toddlers’ mean looking time at test for each condition separately and applied an offset corresponding to chance performance (0.50) to the intercept of the model. For all analyses we report F-statistics.

Anticipatory looks to objects about to be labeled—As a secondary measure of sequence learning, we measured anticipatory looks for Predictable and Unpredictable Events. If toddlers anticipated without regard to predictability, they should be equally accurate in their anticipations for Predictable versus Unpredictable Events. However, if toddlers learned the sequence, they should be more accurate in anticipating the correct box

to open up for Predictable Events than Unpredictable Events. We counted anticipatory looks as looks that occurred during the ISI for trials in which an object was about to be labeled (see Figure 1B). The critical time window started from the beginning of the ISI to 200 ms after the ISI ended (and the box cover had begun to lift, 900 ms in total) to account for the planning of a saccade [54]. We first calculated the overall proportion of anticipatory shifts per child by dividing the total number of anticipatory shifts (shifts that occurred within the critical time window, regardless of accuracy) by the total number of labeling trials. In Experiment 1, the overall proportion of anticipatory shifts was equal for Predictable ($M = 0.37$, $SD = 0.27$) and Unpredictable Events [$M = 0.39$, $SD = 0.26$; $F(1,49) = 0.44$, $p = 0.51$]. This effect was replicated in Experiment 2 [Predictable Events: $M = 0.32$ $SD = 0.23$; Unpredictable Events: $M = 0.32$ $SD = 0.22$; $F(1,56) = 0.008$, $p = 0.93$].

We next calculated the accuracy of these anticipatory shifts. A correct anticipatory shift consisted of a saccade to the box that would be opening. An incorrect anticipatory shift consisted of a saccade to one of the other two boxes. We calculated the proportion of correct anticipatory shifts, out of all anticipatory trials, for both Unpredictable and Predictable Events. For these analyses, we only included children who made anticipatory shifts on at least 1 trial for both Predictable and Unpredictable Events (Experiment 1: $n = 38$; Experiment 2: $n = 44$). In Experiment 1, toddlers made significantly more accurate anticipatory shifts for Predictable Events ($M = 0.40$, $SD = 0.35$) than Unpredictable Events [$M = 0.09$, $SD = 0.17$; $F(1,37) = 24.37$, $p < 0.001$]. In Experiment 2, we saw the same pattern of results: more accurate anticipatory shifts for Predictable Events ($M = 0.46$, $SD = 0.41$) than Unpredictable Events [$M = 0.10$, $SD = 0.24$; $F(1,43) = 25.0$, $p < 0.001$]. These results suggest that toddlers successfully learned the spatiotemporal pattern, more accurately anticipating the next event in the sequence when it was predictable.

Overall patterns: Combining the test data from Experiments 1 (Block 1) and 2

—Given that Experiment 2 was a replication of Experiment 1 (Block 1), we combined the test data from both experiments to assess overall patterns and to investigate participant variables using a larger dataset. We combined the test data of the final sample of participants for Experiment 1 (Block 1 only) with the final sample of participants for Experiment 2 test data (total $n = 71$). First, we compared test performance against chance. The results from the combined data showed that as a group, participants reliably learned the labels for objects presented during Predictable Events [$M = 0.65$, $SD = 0.17$; $F(1,70) = 56.26$, $p < 0.001$] and for objects presented during Unpredictable Events [$M = 0.55$, $SD = 0.21$; $F(1,70) = 3.9$, $p = 0.05$]. However, there was a significant difference in accuracy for the two types of objects. Children were more accurate for objects labeled during Predictable Events than objects labeled during Unpredictable Events [$F(1, 70) = 14.82$, $p < 0.001$].

We next assessed if there was an effect of Experiment, as well as other participant variables collected (Gender, Vocabulary, and Age), on children's performance. We analyzed four separate models that included the fixed effect of Event Type, the fixed effect of the variable of interest, and the interaction between the two (for age and vocabulary, we split the participants into two groups based on the median of the sample; for vocabulary, we used the raw values from the MCDI). For all models, the fixed effect of Event Type remained significant ($p < 0.05$). None of the other variables (Experiment, Gender, Vocabulary, or Age)

were significant ($p > 0.10$ for all variables), and no interactions between the variables and Event Type were significant ($p > 0.10$ for all interactions).

Linking reaction times during the sequence to accuracy at test—We were interested in whether there was a link between learning of the spatiotemporal pattern and the effects of predictability on accuracy during the test. We asked if children who generated stronger expectations during the spatiotemporal sequence showed greater benefits of predictability on word learning. For this analysis, we used the combined sample from Experiments 1 (Block 1) and 2, and calculated a difference score for two measures. The first difference score involved the difference in reaction times for Predictable and Unpredictable Events when an object was about to be labeled within the spatiotemporal pattern (RT difference score: Unpredictable RT – Predictable RT). The second difference score involved the difference between accuracy scores at test for objects labeled during Predictable and Unpredictable Events (Test Accuracy difference score: Predictable Accuracy – Unpredictable Accuracy). Our reasoning was that if children strongly learned the spatiotemporal pattern, the RT difference score should be large (RT's to Unpredictable Events would be much slower than RTs to the Predictable Events). Similarly, if children were strongly affected by predictability at learning, then the test accuracy difference score should be large. We assessed the link between these two scores by regressing the RT difference score on the Test accuracy difference score. The results showed no significant correlation between the two types of scores [$F(1,69) = 0.01$, $p = 0.89$]. These results suggest no direct link between reaction times during the spatiotemporal sequence and accuracy at test.

DATA AND SOFTWARE AVAILABILITY

Summary spreadsheets and scripts for the main analyses are available at: <https://osf.io/hxqse/>

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Highlights

- Predictability is an important aspect of events in the world
- Both expected and unexpected events may enhance learning in young children
- Toddlers learned words better from predictable events than unpredictable events
- Predictability creates advantageous learning moments for toddlers

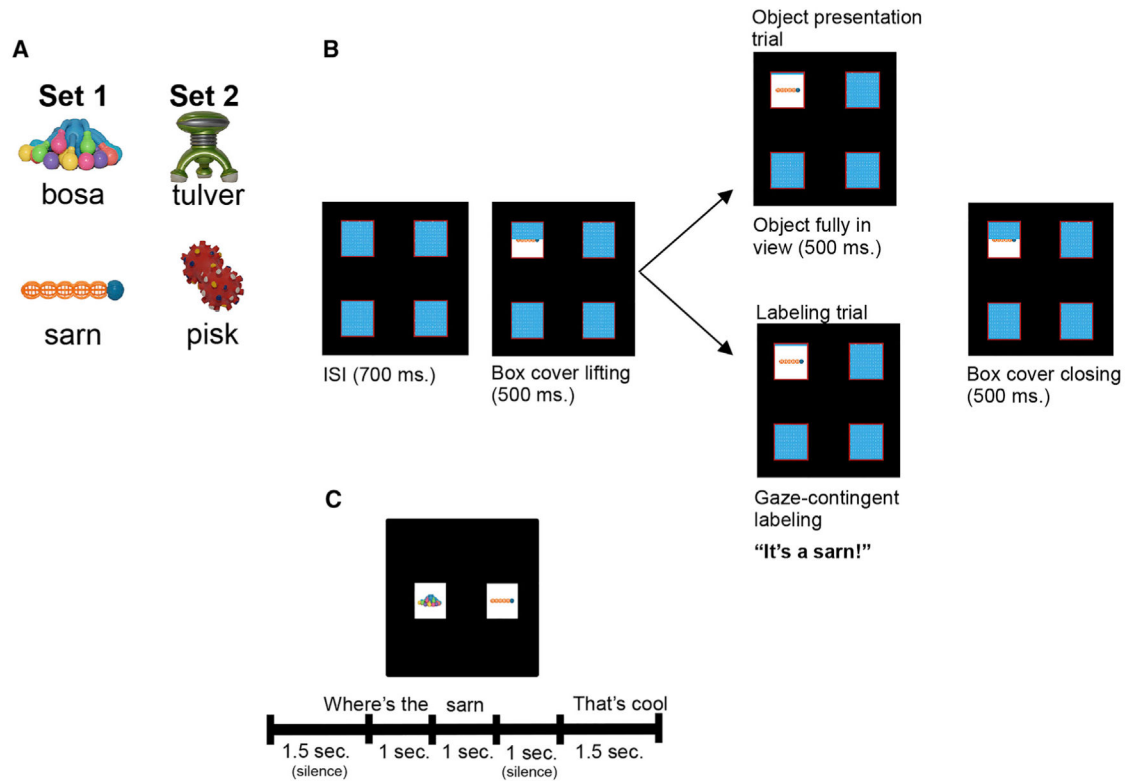


Figure 1. Overview of the Experiment

(A) Novel label-object pairings presented to toddlers within the sequence of events. Each set was labeled at predictable or unpredictable events in the sequence (counterbalanced across children).

(B) One event in the spatiotemporal sequence. The event consisted of an object being revealed from a box at one of four locations. The boxes opened and closed in a sequence (1, 2, 3, 4) beginning with the top left box and moving clockwise to end with the bottom left box. In the sequence-exposure phase, objects were presented without being named (object presentation, top branch). In the sequence-labeling phase, the sequence of events continued to be repeated, with labeling moments interspersed throughout. Labeling moments for the novel objects were embedded in the sequence (labeling, bottom branch). Labeling was gaze contingent, and objects were labeled during either predictable or unpredictable events. See also Videos S1 and S2.

(C) A looking-while-listening trial testing acquisition of the word-object pairings. Objects were yoked at test so that on any individual trial, children saw a pair of objects that had previously been labeled during either predictable events or unpredictable events.

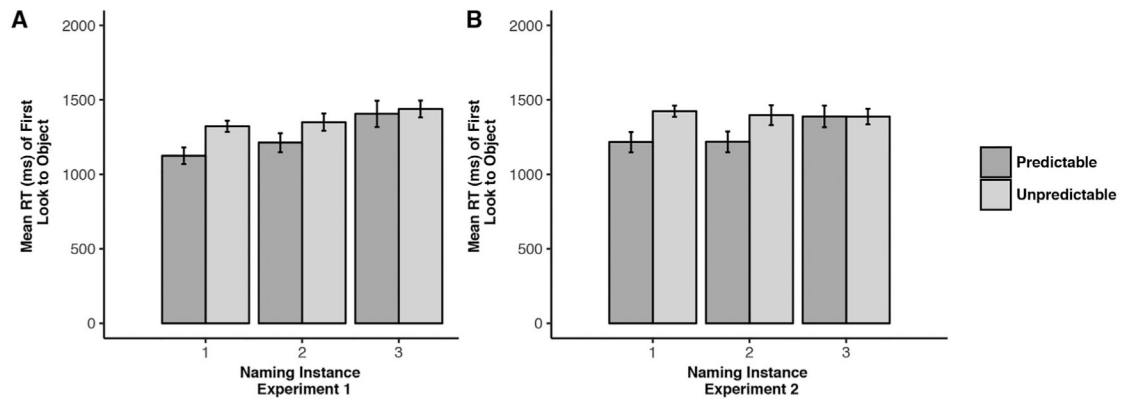


Figure 2. Look Reaction Times to Objects during Predictable and Unpredictable Events (A and B) Mean RTs (SE) of the first look to the objects being revealed at predictable or unpredictable events for the first, second, and third naming instances for (A) experiment 1 and (B) experiment 2.

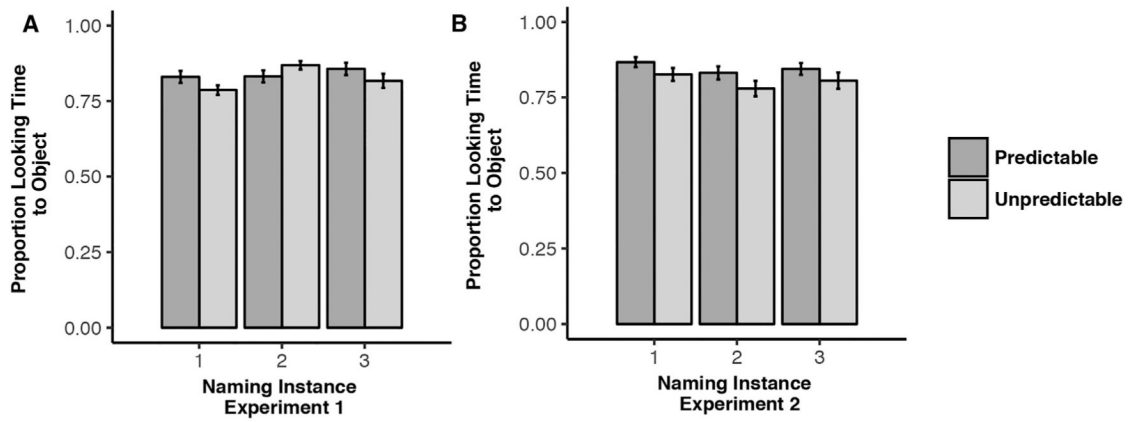


Figure 3. Overall Looking Time to Objects Labeled during Predictable and Unpredictable Events

(A and B) Mean proportion looking time (SE) to objects presented at predictable or unpredictable events for the first, second, and third naming instances in (A) experiment 1 and (B) experiment 2.

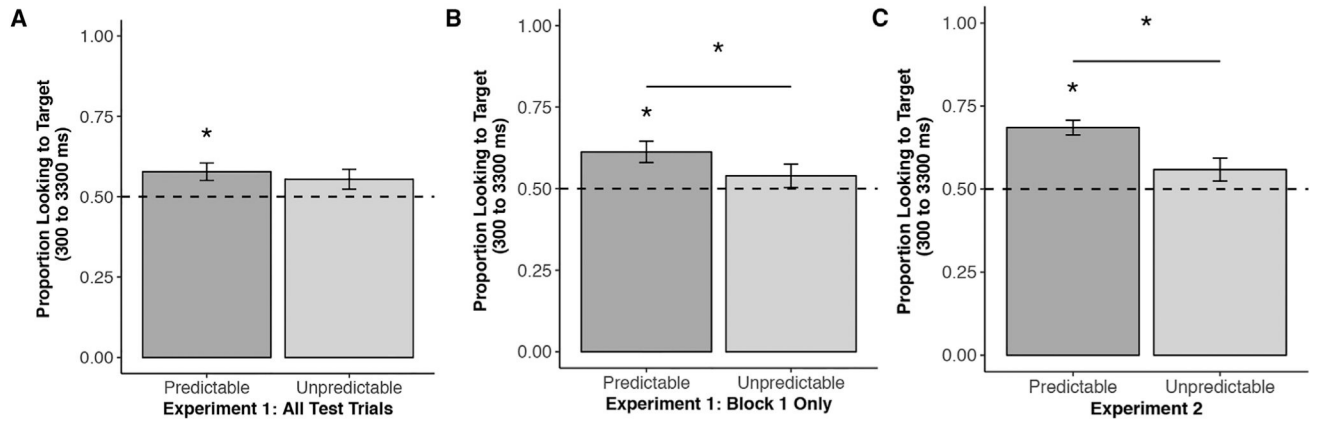


Figure 4. Test Accuracy for Objects Labeled at Predictable and Unpredictable Events
 (A–C) Mean proportion looking time (SE) to the correct target object out of the total time spent looking to both objects during the critical window for objects labeled at predictable events or unpredictable events for (A) experiment 1; (B) experiment 1, block 1; and (C) experiment 2. Dashed line denotes chance level; solid line denotes significant differences between conditions. * $p < 0.05$.

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Deposited Data		
Summary data spreadsheets	This paper	https://osf.io/hxqse/

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