The specificity of sequential Statistical Learning: Statistical Learning accumulates predictive information from unstructured input but is dissociable from (declarative) memory

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Abstract

Learning statistical regularities from the environment is ubiquitous across domains and species. It has been argued to support the earliest stages of language acquisition, including identifying and learning words from fluent speech (word-segmentation). We ask how the Statistical Learning mechanisms involved in word-segmentation interact with the memory mechanisms needed to remember words, if they are tuned to specific learning situations. We show that, when completing a memory recall task after exposure to continuous, statistically structured speech sequences, participants track the statistical structure of the speech stream, but hardly remember any items at all and initiate their productions with random syllables (rather than word-onsets) despite being sensitive to probable syllable transitions. Only discrete familiarization sequences with isolated words produce memories of actual items. Conversely, Statistical Learning predominantly operates in continuous speech sequences like those used in earlier experiments, but not in discrete chunk sequences likely encountered during language acquisition. Statistical Learning might thus be specialized to accumulate distributional information, but dissociable from the (declarative) memory mechanisms needed to acquire words.

Keywords: Statistical Learning; Declarative Memory; Predictive Processing; Language Acquisition

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1 Introduction

The ability to learn statistical regularities from the environment is remarkably widespread across species and domains (Aslin, Saffran, & Newport, 1998; Saffran, Aslin, & Newport, 1996; Hauser, Newport, & Aslin, 2001; Kirkham, Slemmer, & Johnson, 2002; Toro, Trobalon, & Sebastián-Gallés, 2005; Turk-Browne & Scholl, 2009; Chen & Ten Cate, 2015), and might support a wide range of computations, especially during language acquisition (Aslin & Newport, 2012). However, the computational function of statistical learning is unclear. In the context of speech segmentation, Statistical Learning might help learning words from fluent speech (e.g., Aslin et al., 1998; Saffran et al., 1996), and thus, presumably to store word candidates in (declarative) memory (Graf-Estes, Evans, Alibali, & Saffran, 2007; Isbilen, McCauley, Kidd, & Christiansen, 2020). Other authors suggest that Statistical Learning is important for predicting events (Sherman & Turk-Browne, 2020; Turk-Browne, Scholl, Johnson, & Chun, 2010). Here, we suggest that Statistical Learning is critical for predicting speech material and operates predominantly under conditions where prediction is possible. However, we also suggest that Statistical Learning does not lead to (declarative) memories of words, and that separate mechanisms are required to form (declarative) memories of the words.

1.1 Statistical Learning vs. declarative memory of words in fluent speech

Speech is often thought to be a continuous signal (and often perceived as such in unknown languages, but see below), and before learners can commit any words to memory, they need to learn where words start and where they end. They might rely on Transitional Probabilities (TPs) among syllables, that is, the conditional probability of a syllable σ_{i+1} given a preceding syllable σ_i, $P(\sigma_i\sigma_{i+1})/P(\sigma_i)$. Relatively predictable transitions are likely located inside words, while unpredictable ones straddle word boundaries. Early on, Shannon (1951) showed that human adults are sensitive to such distributional information. Subsequent work demonstrated that infants and non-human animals share this ability (Saffran et al., 1996; Hauser et al., 2001; Kirkham et al., 2002; Toro, Trobalon, & Sebastián-Gallés, 2005; Turk-Browne & Scholl, 2009; Chen & Ten Cate, 2015), and that it might reflect simple associative mechanisms such as Hebbian learning (Endress & Johnson, 2021).

Statistical Learning therefore supports predictive processing (Sherman & Turk-Browne, 2020; Turk-Browne et al., 2010), that is, the ability to anticipate stimuli and events based on current and past experience. This ability is critical for language (Levy, 2008; Trueswell, Sekerina, Hill, & Logrip, 1999) and other cognitive processes (Clark, 2013; Friston, 2010; Keller & Mrsic-Flogel, 2018). However, while words are clearly stored in declarative Long-Term Memory (after all, the point of knowing words is to "declare" them), statistical knowledge does not imply the formation of such memory representations. In fact, after exposure to sequences where some transitions are more likely than others, observers report greater familiarity with high-TP items than with low-TP items, even when they have never encountered either of them and thus could not have memorized them

(because the items are played backwards with respect to the familiarization sequence; Endress & Wood, 2011; Turk-Browne & Scholl, 2009; Jones & Pashler, 2007). Sometimes, observers even report greater familiarity with high-TP items they have *never* encountered than with low-TP items they have heard or seen (Endress & Langus, 2017; Endress & Mehler, 2009b).

Dissociations between Statistical Learning and declarative memory have long been documented behaviorally (Graf & Mandler, 1984), developmentally (Finn et al., 2016), and neuropsychologically (Cohen & Squire, 1980; Knowlton, Mangels, & Squire, 1996; Poldrack et al., 2001; Squire, 1992), to the extent that statistical predictions can *impair* declarative memory encoding in healthy adults (Sherman & Turk-Browne, 2020). If Statistical Learning operates similarly in a word-segmentation context as in other learning situations, one would expect it to be dissociable from declarative Long-Term Memory, a view that is reinforced by the suggestion that the format of the representations created by Statistical Learning differs from that used for linguistic stimuli (Endress & Langus, 2017; Fischer-Baum, Charny, & McCloskey, 2011; Miozzo, Petrova, Fischer-Baum, & Peressotti, 2016).

In addition to possible dissociations between Statistical Learning and declarative memory, it is also unclear how continuous fluent speech really is. In fact, due to its prosodic organization, speech does not come as a continuous signal but rather as a sequence of smaller units (Cutler, Oahan, & van Donselaar, 1997; Nespor & Vogel, 1986; Shattuck-Hufnagel & Turk, 1996). This prosodic organization is perceived in unfamiliar languages (Brentari, González, Seidl, & Wilbur, 2011; Endress & Hauser, 2010; Pilon, 1981) and even by newborns (Christophe, Mehler, & Sebastian-Galles, 2001). It might affect the usefulness of Statistical Learning, because such speech cues tend to override

statistical cues (Johnson & Jusczyk, 2001; Johnson & Seidl, 2009), and because Statistical Learning primarily operates *within* rather than across major prosodic boundaries (Shukla, Nespor, & Mehler, 2007; Shukla, White, & Aslin, 2011). As a result, the learner's segmentation task is not so much to integrate distributional information over long stretches of continuous speech, but rather to decide whether the correct grouping in prosodic groups such as "*thebaby*" is "*theba + by*" or "*the + baby*" (though prosodic groups are often longer than just three syllables; Nespor & Vogel, 1986).

1.2 Statistical learning in continuous sequences and discrete chunks

If Statistical Learning mainly supports predictive processing, it might also operate predominantly under conditions that are conducive for prediction, and associations among syllables might form more easily when the syllables are part of a continuous sequence compared to when they are packaged into discrete items (e.g., through prosodic phrasing); after all, longer, continuous sequences provide more information on which predictions can be based than shorter chunks. Preferential Statistical Learning in continuous sequences would be one of numerous examples where Statistical Learning works better over some stimulus classes than others. The classic example is taste aversion, where rats readily associate tastes with sickness and external stimuli with pain but cannot associate taste with pain or external stimuli with sickness (Garcia, Hankins, & Rusiniak, 1974; L. T. Martin & Alberts, 1979; Alberts & Gubernick, 1984); other examples include associations of objects with landmarks vs. boundaries (Doeller & Burgess, 2008), associations among social vs. non-social objects (Tompson, Kahn, Falk, Vettel, & Bassett, 2019), and associations among consonants vs. vowels (Bonatti,

Peña, Nespor, & Mehler, 2005; Toro, Bonatti, Nespor, & Mehler, 2008).[1]

The hypothesis that Statistical Learning predominantly supports predictive processing thus raises the possibility that it might thus operate predominantly in continuous rather than discrete sequences. Conversely, discrete chunks might be more conducive for the formation of declarative memories, because such chunks have clear onsets and offsets, which appears to be a key requirement of the memory representations of linguistic stimuli (Endress & Langus, 2017; Fischer-Baum et al., 2011; Miozzo et al., 2016). The importance of discrete chunks for word learning is support by the finding that a word-segmentation model relying just on information at the edges of discrete chunks (in the form of utterance boundaries) performed better than most other word-segmentation models (Monaghan & Christiansen, 2010), and that statistical information does not always lead to better performance when boundary information is provided (Sohail & Johnson, 2016).

In fact, Statistical Learning is typically explored with continuous sequences. Participants are familiarized with speech sequences consisting of random concatenations of non-sense "words" (or equivalent units in other modalities). As a result, syllables within words are more predictive of one another (and have higher TPs) than syllable combinations that straddle word boundaries. Following such a familiarization, (adult) participants typically complete a two-alternative forced-choice recognition task, where they have to choose between the words from speech stream and part-words. Part-words are tri-syllabic items that straddle a word boundary. For example, if *ABC* and *DEF*

[1] This is not to say that Statistical Learning evolved *for* specific computations; Statistical Learning might still be a "spandrel" (Gould, Lewontin, Maynard Smith, & Holliday, 1979) that evolved as a side effect of local neural processing and might undergo positive, negative or no selection in different brain pathways.

are two consecutive words, *BCD* and *CDE* are the corresponding part-words. Participants tend to choose words over part-words, suggesting that they are sensitive to the greater predictiveness (and TPs) of syllables within words. However, such results still leave open the question of whether participants can use this sensitivity to memorize words from fluent speech, and whether this sensitivity would be present in discrete sequences.

There is some evidence that learners might process continuous speech sequences differently from discrete ones (e.g., Endress & Bonatti, 2016; Marchetto & Bonatti, 2015; Peña, Bonatti, Nespor, & Mehler, 2002). For example, Peña et al. (2002) familiarized participants with continuous speech streams as well as with discrete, "pre-segmented" speech streams, in which each word was followed by a brief silence. The brief silences triggered additional processes such as rule-like generalizations that were unavailable after continuous familiarizations. Critically, the rule-like generalizations observed after pre-segmented familiarizations might reflect memory processes. Endress and Mehler (2009a) suggested that the role of the silences was to act as Gestalt-like grouping cues that provided learners with the location of the word edges (i.e., onsets and offsets), and thus enabled generalizations based on those word-edges (see also Glicksohn & Cohen, 2011; Morgan, Fogel, Nair, & Patel, 2019 for other perceptual grouping effects in Statistical Learning). Given that the grouping cues resulted in a sequence of discrete chunks, the grouping cues might also support declarative memory processing.

1.3 The current experiments

Here, we explore the computational function of Statistical Learning in word-segmentation. In Experiment 1, we ask if Statistical Learning leads to

declarative memory of words. We exposed (adult) participants to the speech stream from Saffran et al.'s (1996) classic word-segmentation experiment. The speech stream consists of four non-sense words randomly concatenated into a continuous speech sequence. As a result, TPs among syllables are higher within words than across word-boundaries. We presented the stream either as a continuous sequence (as in Saffran et al.'s (1996) experiments), or as a pre-segmented sequence of words, with brief silences across word boundaries. As mentioned above, these continuous vs. pre-segmented presentation modes trigger different sets of memory processes (Endress & Bonatti, 2016; Marchetto & Bonatti, 2015; Peña et al., 2002), but it is unknown if either of these processes involves declarative memory. Following this familiarization, we simply asked participants to recall what they remembered from the speech stream. In light of the finding that participants in Statistical Learning tasks sometimes endorse items they have never encountered (e.g., Endress & Wood, 2011; Turk-Browne & Scholl, 2009; Jones & Pashler, 2007) and can endorse them over items they *have* encountered (Endress & Langus, 2017; Endress & Mehler, 2009b), we expected that participants would form declarative memories only after a pre-segmented familiarization.

In Experiment 2, we asked whether Statistical Learning operates in smaller chunks such as those that might be encountered due to the prosodic organization of language, or only in longer stretches of continuous speech. Participants listened to a speech sequence of tri-syllabic non-sense words. As in Experiment 1, the words were either *pre-segmented* (i.e., with a silence after each word) or continuously concatenated.

For half of the participants, both the TPs and the chunk frequency was higher between the first two syllables of the word than between the last two

syllables (TPs of 1.0 vs. .33). A Statistical Learner should thus split triplets like *ABC* into an initial *AB* chunk followed by a singleton *C* syllable (hereafter *AB+C* pattern). For the remaining participants, both the TPs and the chunk frequency favored an *A+BC* pattern. To make the learning task as simple as possible, the statistical pattern of the words was thus consistent for each participant. Following this familiarization, participants heard pairs of *AB* and *BC* items, and had to indicate which item was more like the familiarization items. If Statistical Learning predominantly operates in continuous rather than pre-segmented sequences, participants should split the triplets into their underlying chunks only after continuous but not pre-segmented familiarizations.

To preview our results, in Experiment 1, we find that participants remember words only after listening to pre-segmented speech sequences, but not after listening to the continuous speech sequences usually employed in Statistical Learning tasks. Conversely, in Experiment 2, participants predominantly track TPs in continuous speech sequences, but less so in pre-segmented sequences.

2 Experiment 1: Do learners remember items in a Statistical Learning task?

In Experiment 1, we asked if participants would remember the items that occurred in a speech stream. Adult participants listened to the artificial languages from Saffran et al.'s (1996) Experiment 2 with 8-months-old infants, except that, to increase the opportunity for learning the statistical structure of the speech stream, we doubled the exposure to 90 repetitions of each word. The languages comprised four tri-syllabic words, with a TP of 1.0 within words and 0.33 across word boundaries. The words were presented in a continuous stream or as a pre-segmented word sequence. We ran a lab-based version of the experiment

(Experiment 1a) and an online replication with a larger sample size (Experiment 1b). As the results of both experiments were similar, we present them jointly.

Following a retention interval, participants had to repeat back the words they remembered from the speech stream. Lab-based participants responded vocally, while online participants typed their answer into a comment field. Finally, participants completed a recognition test during which we pitted words against part-words. Part-words are tri-syllabic items that straddle a word-boundary. For example, if *ABC* and *DEF* are two consecutive words, *BCD* and *CDE* are the corresponding part-words. If participants reliably choose words over part-words, they track TPs.

2.1 Materials and methods

2.1.1 Participants. As we had no prior expectation about the effect size, we targeted a sample of at least 30 participants for each of the conditions (i.e., continuous vs. pre-segmented × Language 1 vs. Language 2, see below) in the (laboratory-based) Experiment 1a. This number was chosen because it is realistic in the time-frame available for a third-year honors project. In the (online) Experiment 1b, we tested 50 participants per condition. Participants reported to be native speakers of English, but we did not further assess their English proficiency. At least in Experiment 1a, participants were most likely exposed to English from childhood, as the experiment took place in London, UK, and the experimenters did not notice any clear non-native accents.

To reduce performance differences between the pre-segmented and the continuous familiarization conditions, participants were excluded from analysis if their accuracy in the recognition test was below 50% ($N = 8$ in Experiment 1a; $N = 11$ in Experiment 1b). Another 11 participants were excluded from

Experiment 1b because parsing their productions took an excessive amount of computing time, though their productions did not seem to resemble the familiarization items in the first place. In Experiment 1b, once the final sample of participants in the continuous condition was established, we randomly removed participants from the pre-segmented condition to equate the number of participants across the conditions. (This was not necessary in the within-participant design of Experiment 1a.) The final sample included 26 participants in the lab-based version (Experiment 1a), and 152 in the online version (Experiment 1b). Demographic information is given in Table 1.

Table 1
Demographics of the final sample in Experiments 1 and 2. In Experiment 1a, the (lab-based) participants completed both segmentation conditions. In Experiment 2b, we conducted two independent replications with the same American English voice due to unexpected results with the British English voice in Experiment 2a.

Sequence Type	Voice	N	Females	Male	Age (*M*)	Age (range)
Experiment 1a: Lab-based recall experiment						
continuous	us3	13	13	0	19.2	18-22
pre-segmented	us3	13	13	0	19.2	18-22
Experiment 1b: Online recall experiment						
continuous	us3	76	26	50	30.7	18-71
pre-segmented	us3	76	15	61	28.9	18-62
Experiment 2a – Lab-based segmentation experiment (British English voice)						
pre-segmented	en1	30	22	8	25	18-42
continuous	en1	30	20	10	23.9	18-45
Experiment 2b – Lab-based segmentation experiment (American English voice)						
pre-segmented	us3	30	18	12	26.3	18-43
continuous	us3 (1)	32	26	6	20.1	18-44
continuous	us3 (2)	30	20	10	23.2	18-36

2.1.2 Materials. We re-synthesized the languages used in Saffran et al.'s (1996) Experiment 2. The four words in each language are given in Table 2. Each word was composed of three syllables, which were composed of two

segments in turn. Stimuli were synthesized using the us3 (male American English) voice[2] of the mbrola synthesizer (Dutoit, Pagel, Pierret, Bataille, & van der Vreken, 1996), at a constant F_0 of 120 Hz and at a rate of 216 ms per syllable (108 ms per phoneme).

Table 2
Languages used Experiment 1. The words are the same as in Experiment 2 in Saffran et al. (1996).

L1	L2
pabiku	bikuti
tibudo	pigola
daropi	tudaro
golatu	budopa

During familiarization, words were presented 45 times each. We generated random concatenations of 45 repetitions of the 4 words, with the constraint that words could not occur in immediate repetition. For continuous streams, each randomization was then synthesized into a continuous speech stream (with no silences between words) using mbrola (Dutoit et al., 1996) and then converted to mp3 using ffmpeg (`https://ffmpeg.org/`). For pre-segmented streams, words were synthesized in isolation. Each randomization was then used to concatenate the words into a pre-segmented stream, with silences of 222 ms between words, which was then converted to mp3. Streams were faded in and out for 5 s using sox (`http://sox.sourceforge.net/`). For continuous streams, this yielded a stream duration of 1 min 57 s; for segmented streams, the duration was 2 min 37. Syllable transitions had TPs of 1.0 within words and 0.33 across word boundaries. We created 20 versions of each stream with different random orders

[2] Experiment 1 was chronologically carried out after Experiment 2, but we changed the order for readability. We chose the us3 voice because the alternative en1 (British English) voice introduced artifacts in Experiment 2a.

of words.

As the role of the silences in the pre-segmented stream was to create clearly identifiable chunks, the silence duration was chosen to result in clearly perceptible syllable groups (according to the experimenters' perception). Other investigations with pre-segmented material used shorter silences (e.g., Peña et al., 2002), longer ones (e.g., Sohail & Johnson, 2016; Endress & Mehler, 2009a) or natural prosodic phrasing (Shukla et al., 2007; Seidl & Johnson, 2008). Relatedly, other experiments mimicking the prosodic organization of speech used natural prosodic phrasing (Shukla et al., 2007; Seidl & Johnson, 2008) or grouped several "words" together using silences (Sohail & Johnson, 2016). In the light of Experiment 2, where we ask if Statistical Learning can be used to break up small prosodic groups such as "thebaby" into their underlying words (i.e., "the+baby"), we follow Peña et al. (2002) and present silences after each word instead of inducing longer groupings.

For the online Experiment 1b, the speech streams were combined with a silent video with no clear objects to increase attention to the stimuli. We used a panning of the Carina nebula, obtained from `https://esahubble.org/videos/heic0707g/`. The video was combined with the speech stream using the muxmovie utility.

2.1.3 Apparatus. The lab-based Experiment 1a was run using Psyscope X (`http://psy.ck.sissa.it`) in a quiet room. The online Experiment 1b was run on `https://testable.org`.

2.1.4 Procedure.

2.1.4.1 Familiarization. Participants were informed that they would be listening to an unknown language and that they should try to learn the words from that language. The familiarization stream was presented twice, leading to a

total familiarization duration of 3 min 53 for the continuous streams and 5 min 13 for the segmented streams. They could proceed to the next presentation of the stream by pressing a button.

In the online Experiment 1b, participants watched a video with no clear objects during the familiarization.

Following the familiarization, there was a 30 s retention interval. In both Experiment 1a and 1b, participants were instructed to count backwards from 99 in time with a metronome beat at 3s / beat. Performance was not monitored.

2.1.4.2 Recall test. Following the retention interval, participants completed the recall test. In Experiment 1a, participants had 45 s to repeat back the words they remembered; their vocalizations were recorded using ffmpeg and saved in mp3 format. In Experiment 1b, participants had 60 s to type their answer into a comment field, during which they viewed a progress bar.

2.1.4.3 Recognition test. Following the recall test, participants completed a recognition test during which we pitted words against part-words. The (correct) test words for Language 1 (and part-words for Language 2) were /pAbiku/ and /tibudO/; the (correct) test words for Language 2 (and part-words for Language 1) were /tudArO/ and /pigOlA/. These items were combined into 4 test pairs.

2.1.5 Analysis strategy. As we used performance in the recognition test to filter participants who might not have paid attention to the stimuli, performance in the recognition test in the final sample is not representative of the whole sample, and is thus not analyzed. Therefore, we focus on the participants' recall responses.

In brief, the responses were transformed using a set of substitutions rules to allow for misperceptions (e.g., confusion between /b/ and /p/) or

orthographic variability (e.g., *ea* and *ee* both reflect the sound /i/). Finally, we selected the best matches (according to criteria defined in the next section) to the familiarization stimuli.

In Experiment 1a, the participants' verbal responses were recorded and transcribed by two independent observers. Disagreements were resolved by discussion. Online participants typed their responses directly into a comment box.

We use likelihood ratios to provide evidence for the various null hypotheses. Following Glover and Dixon (2004), we fit the participant averages to (i) a linear model comprising only an intercept and (ii) the null model fixing the intercept to the appropriate baseline level, and evaluated the likelihood of these models after correcting for the difference in the number of parameters using the Bayesian Information Criterion.

2.1.5.1 Processing of responses. Each recall response was analyzed in five steps. First, we applied pre-segmentation substitution rules to make the transcriptions more consistent (see Table 3, "before segmentation", for a complete list of substitution rules). For example, *ea* (presumably as in *tea*) was replaced with *i*. These substitutions were not considered when calculating the derivation length (see below).

Second, responses were segmented into their underlying units. If the response did not contain any commas (,) or semicolons (;), any spaces in the response were used to delineate units. For example, if the response was "*tudaro pigola*", *tudaro* and *pigola* would be accepted as units. If a response contained a semicolon or comma, these were used to delineate units. For each of the resulting units, we verified if they contained additional spaces. If they did, these spaces were removed if further segmenting the units based on the spaces resulted in one

or more single-syllable units (operationalized as a string with a single vowel); otherwise, the units were further sub-divided based on the spaces. The rationale for this algorithm is that responses such as *bee coo tee,two da ra,bout too pa* were likely to reflect the words *bikuti*, *tudaro* and *budopa*.

Third, we removed geminate consonants and applied another set of substitution rules to take into account possible misperceptions (see Table 3). For example, we treated the voiced and unvoiced variety of stop consonants as interchangeable. Specifically, for each "*surface*" form produced by the participants, we generated candidate "*underlying*" forms by recursively applying all substitutions rules and keeping track of the number of substitution rules that were applied to derive an underlying form from a surface form. For each unique candidate underlying form, we kept the shortest derivation.

In some cases, these rules result in multiple possible matches. For example, the transcription *rapidala* might correspond to /rOpidAlA/ or /rOpidOlA/. In such cases, we apply the following criteria (in the following order) to decide which match to choose.

1. Choose the option leading to more or longer chunks that are attested in the speech stream.
2. If multiple options lead to chunks of equal length, choose the option requiring fewer changes with respect to the original transcription.

Fourth, for each candidate underlying form, we identified the longest matching string in the familiarization stream. The algorithm first verified if a form was contained in a speech stream starting with an A, B or C syllable; if the underlying form contained unattested syllables, one syllable change was allowed with respect to the speech streams. If no match was found, two sub-strings were created by clipping the first or the last syllable from the underlying form, and

the search was repeated recursively for each of these sub-strings until a match was found. We then selected the longest match for all substrings.

Fifth, for each surface form, we selected the underlying form among the candidate underlying forms using three criteria:

1. The winning underlying form had the maximal *number of attested syllables* among candidate underlying forms;
2. The winning underlying form had the *maximal length* among candidate underlying forms;
3. The winning underlying form had the *shortest derivation* among candidate underlying forms.

The criteria were applied in this order.

2.1.5.2 Measures of interest. We computed various properties for each underlying form, given the "target" language the participants had been exposed to. All measures provided in the raw data are described in Table S1. For each underlying form, we calculated:

1. the number of syllables;
2. whether it was a word from the target language;
3. whether it was a concatenation of words from the target language;
4. whether it was a single word or a concatenation of words from the target language (i.e., the disjunction of (2) and (3));
5. whether it was a part-words from the target language;
6. whether it was a *complete* concatenation of part-words from the target language (i.e., the number of syllables of the item had to be a multiple of three, without any unattested syllables);
7. whether it was a single part-word or a concatenation of part-words from the target language;

8. whether it was high-TP chunk (i.e., a word with the first or the last syllable missing, after removing any leading or trailing unattested syllables);
9. whether it was a low-TP chunk (i.e., a chunk of the form C_iA_j, after removing lead or trailing unattested syllables;
10. whether it had a "correct" initial syllable;
11. whether it had a "correct" final syllable;
12. whether it was part of the speech stream (i.e., the disjunction of being an attested syllable, being a word or a concatenation thereof, being a part-word or a concatenation thereof, being a high-TP chunk or a low-TP chunk);
13. the average forward TP of the transitions in the form;
14. the *expected* forward TP of the form if form is attested in the speech stream (see below for the calculation);
15. the average backward TP of the transitions in the form.

2.1.5.3 Expected TPs. For items that are *correctly* reproduced from the speech stream, the expected TPs depend on the starting position. For example, the expected TPs for items of at least 2 syllables starting on an initial syllable are (1, 1, 1/3, 1, 1, 1/3, 1, 1, 1/3, . . .); if the item starts on a word-medial syllable, these TPs are (1, 1/3, 1, 1, 1/3, 1, 1, 1/3, 1, . . .).

In contrast, the expected TPs for a random concatenation of syllables are the TPs in a random bigram. For an A or a B syllable, there is only one (out 12) non-zero TP continuation with a TP of 1.0, and the 11 other continuations have a TP of zero. As a result, the random TP is $1.0 \times 1/12 + 0.0 \times 11/12 = 1/12$. For a C syllable, there are 3 (out of 12) possible continuations with a TP of 1/3; the other 9 continuations have a TP of zero. As a result, the random TP is $1/3 \times 3/12 + 0.0 \times 9/12 = 1/12$. On average, the random TP is thus

$(1/12 + 1/12 + 1/12)/3 = 1/12 \approx .083$.

2.1.5.4 Exclusion of responses and participants. There was a considerable number of recall responses containing unattested syllables. The complete list of unattested items is in `segmentation_recall_unattested.xlsx` in the supplementary data. Unattested items are items that are not words, part-words (or concatenations thereof), high- or low-TP chunks, or a single syllable. However, it is unclear if these unattested syllables reflect misperceptions not caught by our substitution rules, typos, memory failures or creative responses. This makes it difficult to analyze these responses. For example, the TPs from and to an unattested syllable are zero. However, if the unattested syllable reflects a misperception or a typo, the true TP would be positive, and our estimates would underestimate the participant's Statistical Learning ability.

Here, we decided to include items with unattested syllables to avoid excluding an excessive number of participants. However, the results after removing such items are essentially identical, with the exception of the TPs in the participants' responses. Given that TPs to and from unattested syllables are zero by definition, TPs after removal of responses containing unattested syllables are much higher.

We also decided to remove single syllable responses, as it is not clear if participants volunteered such responses because they thought that individual syllables reflected the underlying units in the speech streams or because they misunderstood what they were ask to do.

2.2 Results

We present the results in three steps. First, we report some general measures of the recall items to show that participants engage in the task and

track TPs in both the continuous and the pre-segmented condition. Second, we ask whether participants are more likely produce words than part-words. Third, we ask whether participants know where words start and where they end.

2.2.1 General measures: Do participants engage in the task?

As shown in Table 4 and Figures 1a and b, participants produced about 4 items. Neither the number of items produced nor their lengths differed across the segmentation conditions. Critically, and as shown in Table 4 and Figures 2a and b, forward and backward TPs in the participants' responses were significantly greater than the chance level of .083 in both segmentation conditions. These TPs likely underestimate the participants' actual performance, as we included responses with unattested syllables that might reflect misperceptions (and thus lower TPs); after removing such responses, TPs in the participants' responses were about twice as large. Participants were thus clearly sensitive to the TPs in the speech stream.

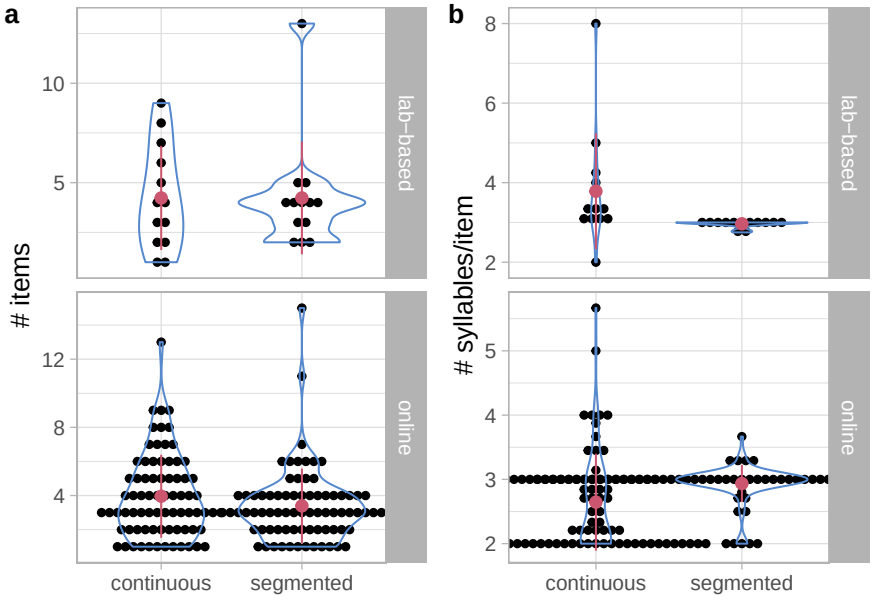

Figure 1. Number of items produced and number of syllables per item in the recall phase of Experiments 1a (top) and 1b (bottom).

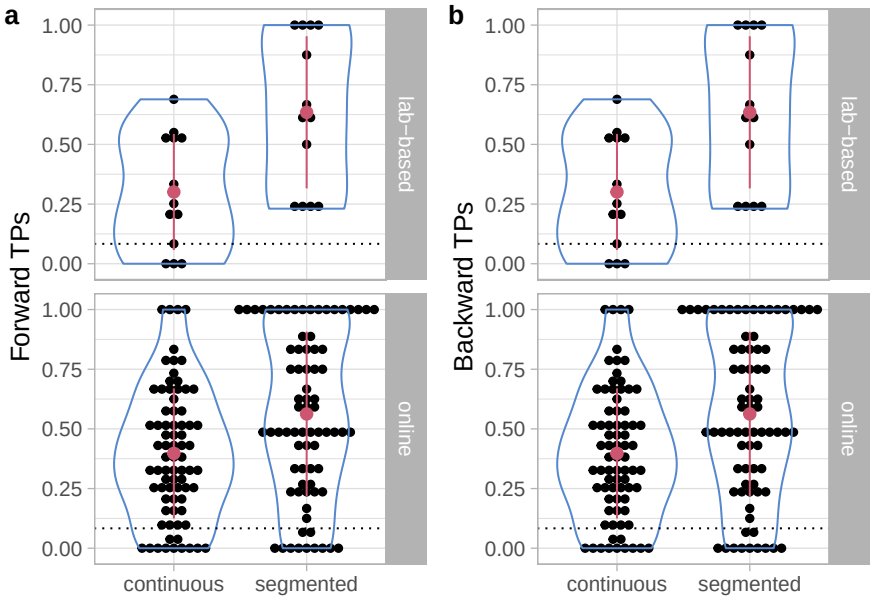

Figure 2. Forward and backward TPs in the participants' productions in the recall phase of Experiments 1a (top) and 1b (bottom). The dotted line represents the chance level for a randomly ordered syllable sequence.

Table 3
Substitution rules applied to the participants vocalizations before and after the input was segmented into chunks. The patterns are given as Perl regular expressions. Substitutions prior to segmentation were intended to make transcriptions more consistent, and were not counted when calculating the derivation length. Substitutions after segmentation allowed for misperceptions, and were counted when calculating derivation length. These substitution rules were motivated by three observations: (1) /O/ might be perceived as /A/. (2) Voiced and unvoiced consonants can be confused; that is /g/ can be confused with /k/, /d/ with /t/ and /b/ and /p/. (3) /b/ might be perceived as /v/.

Before segmentation		After segmentation	
Pattern	Replacement	Pattern	Replacement
\.{3,}		u	o
-		v	b
2	tu	p	b
two	tu	b	p
([aeou])ck	\1k	t	d
ar([,\s+])	a\1	d	t
ar$	a	k	g
tyu	tu	g	k
ph	f	a	o
th	t		
qu	k		
ea	i		
ou	u		
aw	a		
ai	a		
ie	i		
ee	i		
oo	u		
e	i		
c	k		
w	v		
y	i		
h			

We next examined the production of two-syllable chunks. Such chunks can be either high-TP chunks (if they are part of a word) or low-TP chunks (if they straddle a word boundary). For example, with two consecutive words *ABC* and *DEF*, the high-TP chunks are *AB*, *BC*, ..., while the low-TP chunk is *CD*. As a result, two-syllable items have a 66% probability of being a high-TP chunk. As shown in Figure 3b, the proportion of high-TP among chunks high- and low-TP chunks exceeded chance in both the pre-segmented condition and the continuous condition n Experiment 1b (though not in the continuous condition of Experiment 1a), with a significantly higher proportion in the pre-segmented versions. These results thus confirm that participants are sensitive to TPs or high frequency chunks (which are confounded in the current design).

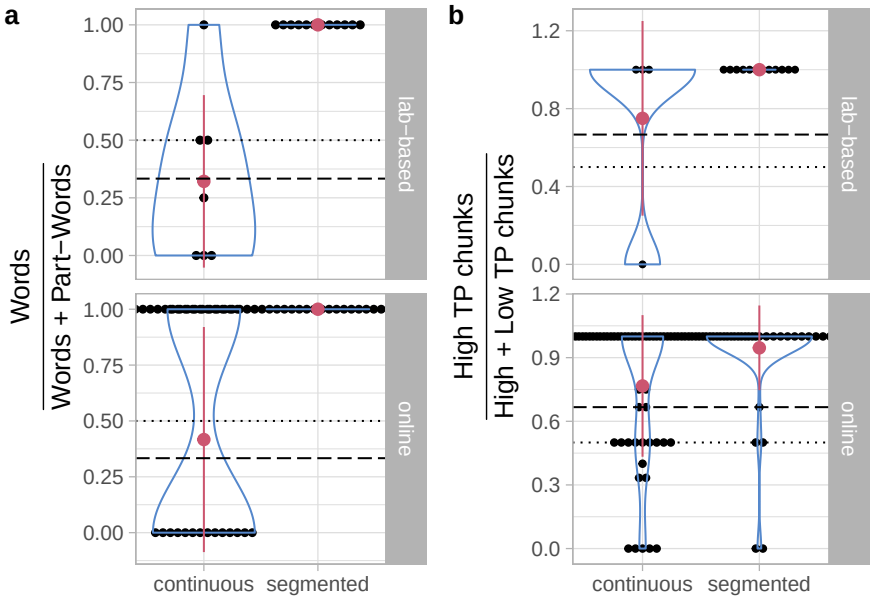

Figure 3. Analyses of the participants' productions in the recall phase of Experiments 1a (top) and 1b (bottom). (a) Proportion of words among words and part-words. The dotted line represents the chance level of 50% in a two-alternative forced-choice task, while the dashed line represents the chance level of 33% that an attested 3 syllable-chunk is a word rather than a part-word. (b) Proportion of high-TP chunks among high- and low-TP chunks. The dashed line represents the chance level of 66% that an attested 2 syllable-chunk is a high-TP rather than a low-TP chunk.

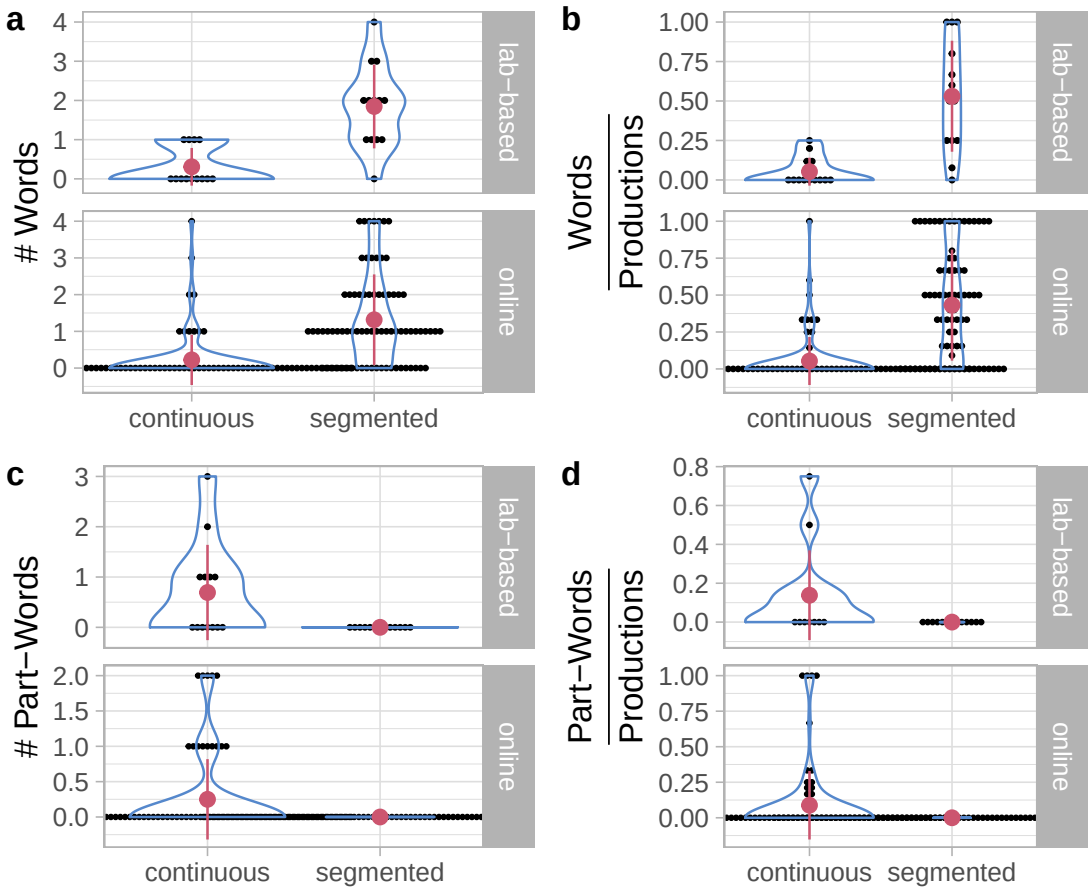

Figure 4. Number and proportion (among vocalizations) of words and part-words in the recall phase of Experiments 1a (top) and 1b (bottom).

2.2.2 Are participants more likely to produce words rather than part-words?

We now turn to the question of whether a sensitivity to TPs

implies memory for words. We address this issue in two ways, by using the traditional contrast between words and part-words and by turning to the question at the heart of word segmentation — do participants know where words start and where they end?

The traditional analysis of word segmentation experiments relies on the contrast between words and part-words. As mentioned above, part-words are tri-syllabic items that straddle a word-boundary. We thus calculated the proportion of words among words and part-words recalled by the participants. If participants faithfully produce trisyllabic sequences from the stream, they can start the sequences on the first, second or third syllable of a word, but only the first possibility yields a word rather than a part-word. As a result, if participants initiate their productions with a random syllable, a third of their productions should be words.

As shown in Table 4 and in Figure 3a, the proportion of words among words and part-words was close to 100% in the pre-segmented conditions, but did not differ from the chance level of 33% in the continuous conditions. Likelihood ratio analysis suggests that, in the continuous condition of Experiment 1b, participants were 3.5 times more likely to perform at the chance level of 33% than to perform at a level different from chance; in Experiment 1a, the likelihood ratio was 2.6. These results thus suggest that participants in the continuous condition initiate their productions at random positions in the stream, and that they do not remember any word forms.

However, inspection of Figure 3a shows that the distribution in the continuous condition is bimodal, with some participants producing only words, and others producing only part-words. Such a behavior can arise if participants pick a syllable as their starting-point, and segment the rest of the stream

accordingly. If they happen to pick a word-initial syllable, they will produce only words; if they pick the second or the third syllable of a word, all subsequent items will be part-words.

Assuming that the number of participants producing words vs. part-words is binomially distributed, we calculated the likelihood ratio of a model where learners identify word boundaries (and should produce words with probability 1), and a model where they track TPs and initiate productions at random positions (and should produce words with a probability of 1/3). As shown in SOM3, the likelihood ratio in favor of the first model is 3^{N_W} if participants produce no part-words (i.e., after a pre-segmented familiarization), where N_W is the number of participants producing words; otherwise, the likelihood ratio in favor of the second model is infinity. Given that the overwhelming majority of participants produce words only after a pre-segmented familiarizations, these results thus suggest that, despite their ability to track TPs, participants initiate productions at random positions in the sequence, and thus do not remember statistically defined words.

However, as shown in Figure 4, these results might be misleading because, in the continuous condition, many participants produce neither words *nor* part-words. In fact, on average, they produce only .4 words and part-words combined, respectively. (In the pre-segmented condition, most participants produce at least one word, with an average of 1.26.)

We thus turn to the question of whether participants know where words start and end, asking if participants produce correct initial and final syllables.

2.2.3 Do participants know where words start and where they end? If participants use Statistical Learning to remember words, they should know where words start and where they end. In contrast, if they just track TPs,

they should initiate the responses with random syllables. As there are four words with one correct initial and final syllable each, and 12 syllables in total, $4/12 = 1/3$ of the productions should have "correct" initial syllables, and 1/3 should have correct final syllables. Given that participants tend to produce high-TP two-syllable chunks (i.e., *AB* and *BC* rather than *CD* chunks), the actual baseline level is somewhat higher.[3] However, to evaluate the group performance, we keep the baseline of 1/3.

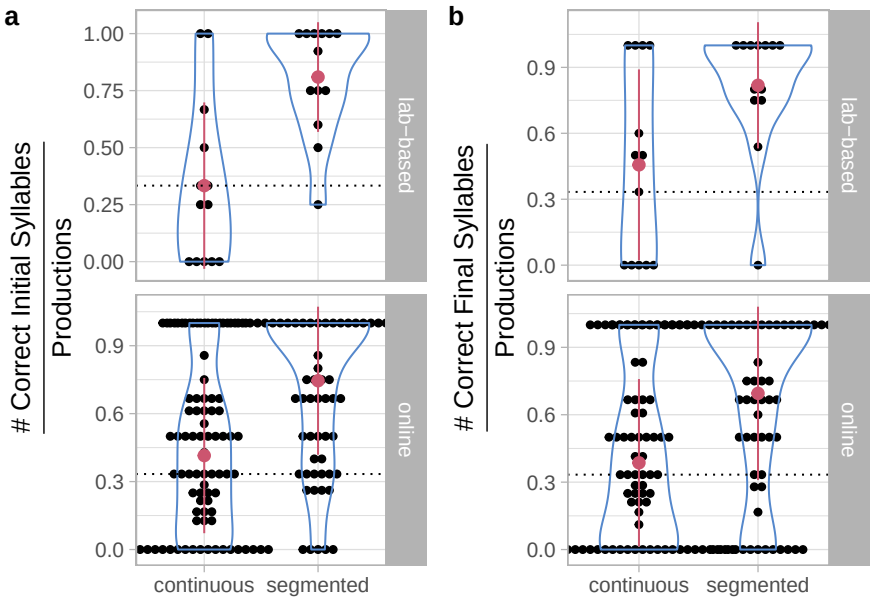

Figure 5. Analyses of the participants' productions in the recall phase of Experiments 1a (top) and 1b (bottom). (a) Proportion of productions with correct initial syllables and (b) with correct final syllables. The dotted line represents the chance level of 33%.

As shown in Table 4 and Figure 5a and b, participants produced items with correct initial or final syllables at greater than chance level only in the pre-segmented conditions, but not in the continuous conditions. In the continuous condition of Experiment 1b, the likelihood ratio in favor of the null

[3] For example, participants in the continuous condition produce about 75% high-TP chunks; if they initiate their productions with high-TP chunks, one would expect them to produce about $75\%/2 = 3/8$ rather than 1/3 items with correct initial syllables.

hypothesis was 0.785 for initial syllables and 4.06 for final syllables; in Experiment 1b, the likelihood ratios are 3.61 and 2.14, respectively. While it is possible that performance in the continuous condition might exceed the chance-level of 1/3 with more than the 78 participants currently included, the actual chance-level is somewhat higher (about 38.4%). Critically, only 42% of the productions have a correct initial syllable, which is unexpected if participants knew where words start and where they end. Together with the finding that the overwhelming majority of participants produce no word at all, these results thus suggest that TPs do not allow learners to reliably detect onsets and offsets of words.

Table 4

Main analyses pertaining to the productions as well as test against their chances levels in the recall phase of Experiments 1a and 1b. The p value in the rightmost column reflects a Wilcoxon test comparing the continuous and the pre-segmented conditions.

	Continuous	Pre-segmented	p(continuous vs. pre-segmented)
Number of items			
lab-based (Exp. 1a)	M= 4.23, SE= 0.756, p= 0.0016	M= 4.23, SE= 0.818, p= 0.00152	0.812
online (Exp. 1b)	M= 4.03, SE= 0.292, p= 3.17e-14	M= 3.25, SE= 0.202, p= 2.74e-14	0.099
Number of syllables/item			
lab-based (Exp. 1a)	M= 3.79, SE= 0.421, p= 0.0016	M= 2.97, SE= 0.0246, p= 0.0007	0.026
online (Exp. 1b)	M= 2.65, SE= 0.0869, p= 2.29e-14	M= 2.93, SE= 0.0364, p= 1.04e-15	< 0.001
Forward TPs			
lab-based (Exp. 1a)	M= 0.301, SE= 0.0702, p= 0.0107	M= 0.634, SE= 0.092, p= 0.00159	0.006
online (Exp. 1b)	M= 0.397, SE= 0.0316, p= 6.26e-12	M= 0.583, SE= 0.04, p= 3.82e-13	0.001
Backward TPs			
lab-based (Exp. 1a)	M= 0.301, SE= 0.0702, p= 0.0107	M= 0.634, SE= 0.092, p= 0.00159	0.006
online (Exp. 1b)	M= 0.397, SE= 0.0316, p= 6.26e-12	M= 0.583, SE= 0.04, p= 3.82e-13	0.001
Proportion of High-TP chunks among High- and Low-TP chunks			
lab-based (Exp. 1a)	M= 0.75, SE= 0.289, p= 0.85 (vs. 2/3)	M= 1, SE= 0, p= 0.0006 (vs. 2/3)	1.000
online (Exp. 1b)	M= 0.767, SE= 0.0459, p= 0.00154 (vs. 2/3)	M= 0.97, SE= 0.0187, p= 6.75e-13 (vs. 2/3)	< 0.001
Proportion of words among words and part-words (or concatenations thereof)			
lab-based (Exp. 1a)	M= 0.321, SE= 0.153, 0.798 (vs. 1/3)	M= 1, SE= 0, p= 0.0006 (vs. 1/3)	0.034
online (Exp. 1b)	M= 0.417, SE= 0.105, p= 0.189 (vs. 1/3)	M= 1, SE= 0, p= 2.08e-13 (vs. 1/3)	< 0.001
Proportion of items with correct initial syllables			
lab-based (Exp. 1a)	M= 0.333, SE= 0.105, p= 0.856	M= 0.809, SE= 0.0694, p= 0.00186	0.016
online (Exp. 1b)	M= 0.419, SE= 0.0392, p= 0.0864	M= 0.738, SE= 0.0387, p= 1.58e-11	0.000
Proportion of items with correct final syllables			
lab-based (Exp. 1a)	M= 0.456, SE= 0.125, p= 0.5	M= 0.818, SE= 0.0829, p= 0.00222	0.025
online (Exp. 1b)	M= 0.386, SE= 0.043, p= 0.456	M= 0.7, SE= 0.0437, p= 4.14e-10	0.000

2.3 Discussion

Experiment 1 provided the first direct test of the contents of the participants' (episodic or semantic) declarative memory after exposure to a Statistical Learning task. The results suggest that, even when participants successfully track statistical information, they remember familiarization items only when familiarized with a pre-segmented sequence. In contrast, when familiarized with a continuous sequence, their productions start with random syllables rather than actual word onsets. Given that the memory representations of linguistic items are based on their initial and final syllables (Endress & Langus, 2017; Fischer-Baum et al., 2011; Miozzo et al., 2016), this result thus suggests that Statistical Learning did not lead to the creation of declarative memory representations.

Contrary to this conclusion, some authors suggest that Statistical Learning might lead to declarative memories for chunks (Graf-Estes et al., 2007; Hay, Pelucchi, Graf Estes, & Saffran, 2011; Isbilen et al., 2020). Such experiments generally proceed in two phases. During a Statistical Learning phase, participants are exposed to some statistically structured sequence. Then, they are exposed to items presented in isolation, and show some processing advantage for isolated high-probability items compared to isolated low-probability items. However, we proposed that such experiments have a two-step explanation that does not involve declarative memory (Endress & Langus, 2017). First, during the Statistical Learning phase, participants acquire statistical knowledge without remembering any specific items. When experimenters subsequently provide participants with *isolated* chunks, the accumulated statistical knowledge facilitates processing of the experimenter-provided chunks (e.g., due to predictive processing), without these chunks having been acquired before being supplied by

the experimenter. In contrast to such indirect designs, we provide a direct measure of declarative knowledge of sequence items, and show that participants do not form declarative memories of sequence items unless the sequence is pre-segmented.

3 Experiment 2: Is Statistical Learning available in both continuous and pre-segmented speech ?

Experiment 1 suggests that participants do not form declarative memory traces of words when the only available cues are statistical in nature. In contrast, they readily form declarative memories when items are pre-segmented.

These results do not imply that Statistical Learning might not play a critical role in word segmentation. As mentioned above, speech is prosodically organized (Cutler et al., 1997; Nespor & Vogel, 1986; Shattuck-Hufnagel & Turk, 1996), and a learner's segmentation task is not so much to integrate distributional information over long stretches of continuous speech, but rather to decide whether the correct grouping in prosodic groups such as "*thebaby*" is "*theba + by*" or "*the + baby*". In principle, Statistical Learning might be well suited to this task. In line with the two-step explanation of Graf-Estes et al.'s (2007), Hay et al.'s (2011), Isbilen et al.'s (2020) experiments above, implicit knowledge of statistical regularities might help learners acquire words more effectively once (prosodic) segmentation cues are given (but see e.g. Ngon et al., 2013; Sohail & Johnson, 2016).

We test this issue in Experiment 2. Participants listened to a speech sequence of tri-syllabic non-sense words. For half of the participants, both the TPs and the chunk frequency were higher between the the first two syllables of the word than between the last two syllables. We thus expected learners to split

a triplet like *ABC* into an *AB+C* pattern. For the remaining participants, both the TPs and the chunk frequency favored an *A+BC* pattern. In the *pre-segmented* condition, the words were presented separated from each other and with a silence after each word. In the *continuous* condition, they were continuously concatenated. Following this familiarization, participants heard pairs of *AB* and *BC* items and had to indicate which item was more like the familiarization items. In Experiment 2a, stimuli were synthesized with the en1 (British English male) voice, though this voice turned out to produce artifacts in the continuous stream. In Experiment 2b, stimuli were synthesized using the us3 (American English male) voice.

If Statistical Learning allows learners to extract "correct" syllable groupings, they should recognize high-frequency chunks after both continuous and pre-segmented familiarizations. In contrast, if Statistical Learning predominantly supports predictive processing (Sherman & Turk-Browne, 2020; Turk-Browne et al., 2010), participants should extract high frequency groupings predominantly after continuous familiarizations in the *continuous* condition.

3.1 Material and Methods

We prepared two versions of Experiment 2, differing in the voice used to synthesize the stimuli. In Experiment 2a, we used a British English male (en1) voice. In Experiment 2b, we used an American English male (us3) voice. Both experiments were lab-based.

3.1.1 Participants. Participants were recruited from the City, University London participant pool and received course credit or monetary compensation for their time. We targeted 30 participants per experiment (15 per language). This number was chosen because it is realistic in the time-frame

available for a third-year honors project. Participants reported to be native speakers of English, but we did not assess their English proficiency. However, participants were most likely exposed to English from childhood, as the experiment took place in London, UK, and the experimenters did not notice any clear non-native accents in most participants and excluded the few participants with non-native accents from analysis. The final demographic information is given in Table 1. In Experiment 2a, an additional 3 participants took part in the experiment but were not retained for analysis because they were much older than the rest of the sample ($N = 3$) or because they had a noticeable non-native accent $N = 1$. In Experiment 2b, an additional six participants were excluded from analysis because they had taken part in a prior version of this experiment ($N = 4$), were much older than the rest of our sample ($N = 2$), or used their phone during the experiment or were visibly inattentive ($N = 2$).

3.1.2 Design. Participants were familiarized with a sequence of tri-syllabic words. In Language 1, both the TPs and the chunk frequency were higher in the bigram formed by the first two syllables than in the bigram formed by the last two syllables. As a result, a Statistical Learner should split a triplet like ABC into an initial AB chunk followed by a singleton C syllable (hereafter $AB{+}C$ pattern). In Language 2, both the TPs and the chunk frequency favored an $A{+}BC$ pattern. The basic structure of the words is shown in Table 5.

As a result, in Language 1, the first bigram has a (forward and backward) TP of 1.0, while the second bigram has a (forward and backward) TP of .33. In contrast, in Language 2, the first bigram has a (forward and backward) TP of .33, while the second bigram has a (forward and backward) TP of 1.0. Likewise, the initial bigrams were three times as frequent as the final ones for Language 1, while the opposite holds for Language 2.

We asked whether participants would extract initial bigrams or final bigrams. The test items are given in Table 5.

3.1.3 Stimuli. Stimuli in Experiment 2a were synthesized using the *en1* (British English male) voice from mbrola (Dutoit et al., 1996). However, as discussed below, it turned out to be of relatively low quality and introduced artifacts in the data. Stimuli in Experiment 2b were synthesized using the *us3* voice (American English male) voice from mbrola (Dutoit et al., 1996).

Segments had a constant duration of 60 ms (syllable duration 120 ms) with a constant F_0 of 120 Hz. These values were chosen to match recordings of natural speech that were intended to be used in investigations of prosodic cues to word segmentation.

For continuous streams, a single file with 45 repetitions of each word was synthesized for each language (2 min 26 s duration). It was faded in and out for 5 s using sox (`http://sox.sourceforge.net/`) and then compressed to an mp3 file using ffmpeg (`https://ffmpeg.org/`). The stream was then presented 3

Table 5
Design of Experiment 2. (Left) Language structure. (Middle) Structure of test items. Correct items for Language 1 are foils for Language 2 and vice versa. (Right) Actual items in SAMPA format; dashes indicate syllable boundaries.

Word structure for		Test item structure for		Actual words for	
Language 1	Language 2	Language 1	Language 2	Language 1	Language 2
ABC	ABC	AB	BC	w3:-le-gu:	w3:-le-gu:
ABD	FBC	FG	GD	w3:-le-vOI	faI-le-gu:
ABE	HBC	HJ	JE	w3:-le-nA:	rV-le-gu:
FGC	AGD			faI-zO:-gu:	w3:-zO:-vOI
FGD	FGD			faI-zO:-vOI	faI-zO:-vOI
FGE	HGD			faI-zO:-nA:	rV-zO:-vOI
HJC	AJE			rV-b{-gu:	w3:-b{-nA:
HJD	FJE			rV-b{-vOI	faI-b{-nA:
HJE	HJE			rV-b{-nA:	rV-b{-nA:

times to a participant (total familiarization duration: 7 min 17 s). The random order of the words was different for every participant.

For segmented streams, words were individually synthesized using mbrola. We then used a custom-made Perl script to randomize the words for each participant and concatenate them into a familiarization file using sox. The order of words was then randomized for each participant and concatenated into a single aiff file using sox. The silence among words was 540 ms (1.5 word durations). The total stream duration was 6 min 12s. The stream was then presented 3 times to a participant (total familiarization: 18 min 14 s).

3.1.4 Apparatus. The experiment was run using Psyscope X (`http://psy.ck.sissa.it`). Stimuli were presented over headphones in a quiet room. Responses were collected from pre-marked keys on the keyboard.

3.1.5 Procedure. Participants were informed that they would listen to a monologue by a talkative Martian, and instructed to try to remember the Martian words. Following this, they listened to three repetitions of the familiarization stream described above, for a total familiarization duration of 7 min 17 s (continuous stream) or 18 min 14 s (segmented stream).

Following this familiarization, participants were presented with pairs of items with an inter-stimulus interval of 500 ms, and had to choose which items was more like what they heard during familiarization. One item comprised the first two syllables of a word, and was a correct choice for Language 1. The other item comprised the last two syllables of a word, and was a correct choice for Language 2. There were three items of each kind. They were combined into 9 test pairs. The test pairs were presented twice, with different item orders, for a total of 18 test trials.

3.1.6 Analysis strategy. Accuracy was averaged for each participant, and the scores were tested against the chance level of 50% using Wilcoxon tests. Performance differences across the languages (Language 1 vs. 2) and, when applicable, familiarization conditions (pre-segmented vs. continuous) were assessed using a generalized linear mixed model for the trial-by-trial data with the fixed factors language and, where applicable, familiarization condition, as well as random slopes for participants, correct items and foils. Following (Baayen, Davidson, & Bates, 2008), random factors were removed from the model when they did not contribute to the model likelihood.

We use likelihood ratios to provide evidence for the null hypothesis that performance did not differ from the chance level of 50%. Following Glover and Dixon (2004), we fit the participant averages to (i) a linear model comprising only an intercept and (ii) the null model fixing the intercept to the appropriate baseline level, and evaluated the likelihood of these models after correcting for the difference in the number of parameters using the Bayesian Information Criterion.

3.2 Results

3.2.1 Experiment 2a (British English voice). We first report the results from Experiment 2a, using a British English voice. When the familiarization stream was pre-segmented, participants failed to split smaller utterances into their underlying components. As shown in Figure 6 (top), the average performance did not differ significantly from the chance level of 50% when the stream was synthesized with the *en1* voice ($M = 54.26$, $SD = 25.09$), Cohen's $d = 0.17$, $CI_{.95} = 44.89, 63.63$, ns. Likelihood ratio analysis favored the null hypothesis by a factor of 3.55 after correction with the Bayesian Information

Criterion. Further, as shown in Table 6, performance did not depend on the language condition.

In contrast to the common finding that humans and other animals are sensitive to TPs, our participants failed to use TPs to split pre-segmented utterances into their underlying units. We thus asked if, in line with previous research, they can track TPs units are embedded into a *continuous* speech stream. That is, participants in the continuous condition listened to the very same artificial speech stream as in the pre-segmented condition, except that the stream was continuous and had no silences between words.

Participants also failed to use TPs to segment words when the speech stream was continuous. Specifically, and as shown in Figure 6 (top), the average performance did not differ significantly from the chance level of 50%, (M = 48.89, SD = 19.65), $t(29)$ = -0.31, p = 0.759, Cohen's d = 0.057, $CI_{.95}$ = 41.55, 56.23, ns, V = 166, p = 0.818. Likelihood analyses revealed that the null hypothesis was 5.22 times more likely than the alternative hypothesis after a correction with the Bayesian Information Criterion. However, as shown in Table 6, performance was much better for Language 1 than for Language 2, presumably due to some click-like sounds the synthesizer produced for some stops and fricatives (notably /f/ and /g/). These sounds likely affected grouping, and prevented participants from using Statistical Learning. We thus decided to replicate Experiment 2a with a different, American English voice.

3.2.2 Experiment 2b (American English voice). When the familiarization stream was pre-segmented, participants failed to split smaller utterances into their underlying components. As shown in Figure 6 (bottom), the average performance did not differ significantly from the chance level of 50% when the stream was synthesized with the *us3* voice (M = 51.67, SD = 15.17),

$V = 216$, $p = 0.307$. Likelihood ratio analysis favored the null hypothesis by a factor of 4.57 after correction with the Bayesian Information Criterion. As shown in Table 6, performance did not depend on the language condition. However, Figure 6 also shows a clearly defined outlier. In Supplementary Information SOM4, we remove participants for Experiments 2a and 2b who differ by more than 2.5 standard deviations from the condition mean. This analysis yields similar results to the unfiltered analyses.

The failure to use Statistical Learning to split pre-segmented units was conceptually replicated in a pilot experiment with Spanish/Catalan speakers using chunk frequency and backwards TPs as the primary cues (SOM5).

Table 6
Performance differences across familiarization conditions in Experiment 2. The differences were assessed using a generalized linear model for the trial-by-trial data, using participants, correct items and foils as random factors. Random factors were removed from the model when they did not contribute to the model likelihood.

		Log odds			Odds ratios				
Term	Voice	Estimate	*SE*	*CI*	Estimate	*SE*	*CI*	*t*	*p*
Pre-segmented familiarization, British English voice (Exp. 2a)									
language = L2	en1	-0.097	0.441	[-0.96, 0.767]	0.908	0.400	[0.383, 2.15]	-0.22	0.826
Continuous familiarization, British English voice (Exp. 2a)									
language = L2	en1	-1.024	0.410	[-1.83, -0.22]	0.359	0.147	[0.161, 0.803]	-2.50	0.013
Pre-segmented vs. continuous familiarization, British English voice (Exp. 2a)									
language = L2	en1	-1.061	0.382	[-1.81, -0.313]	0.346	0.132	[0.164, 0.732]	-2.779	0.005
stream type = segmented	en1	-0.242	0.360	[-0.949, 0.464]	0.785	0.283	[0.387, 1.59]	-0.673	0.501
language = L2 × stream type = segmented	en1	0.967	0.508	[-0.0292, 1.96]	2.631	1.338	[0.971, 7.13]	1.903	0.057
Pre-segmented familiarization, American English voice (Exp. 2b)									
language = L2	us3	0.114	0.673	[-1.2, 1.43]	1.121	0.754	[0.3, 4.19]	0.170	0.865
Continuous familiarization (1), American English voice (Exp. 2b)									
language = L2	us3	-0.184	0.480	[-1.12, 0.757]	0.832	0.400	[0.325, 2.13]	-0.383	0.702
Continuous familiarization (2), American English voice (Exp. 2b)									
language = L2	us3	0.317	0.786	[-1.22, 1.86]	1.372	1.079	[0.294, 6.4]	0.403	0.687
Pre-segmented vs. continuous familiarization, American English voice (Exp. 2b, 1)									
language = L2	us3	-0.019	0.558	[-1.11, 1.07]	0.982	0.547	[0.329, 2.93]	-0.033	0.973
stream type = segmented	us3	-0.328	0.188	[-0.696, 0.0391]	0.720	0.135	[0.499, 1.04]	-1.752	0.080
Pre-segmented vs. continuous familiarization, American English voice (Exp. 2b, 2)									
language = L2	us3	0.215	0.657	[-1.07, 1.5]	1.240	0.814	[0.342, 4.49]	0.327	0.743
stream type = segmented	us3	-0.608	0.244	[-1.09, -0.13]	0.544	0.133	[0.337, 0.878]	-2.493	0.013

As in Experiment 2a, and in contrast to the common finding that humans and other animals are sensitive to TPs, our participants failed to use TPs to

split pre-segmented utterances into their underlying units. We thus asked if they could track TPs units that are embedded into a *continuous* speech stream. As in Experiment 1a, participants in the continuous condition listened to the very same artificial speech stream as in the pre-segmented condition, except that the stream was continuous and had no silences between words.

As shown in Figure 6 (bottom), when the speech stream was synthesized with the *us3* voice, the average performance differed significantly from the chance level of 50%, ($M = 58.51$, $SD = 16.21$), Cohen's $d = 0.52$, $CI_{.95} = 52.66$, 64.35, $V = 306.5$, $p = 0.02$. As shown in Table 6, performance did not depend on the language condition, and was marginally better than in the pre-segmented condition ($p = .08$).

Given the likely confound introduced by the voice used in Experiment 2a, we sought to ensure that the results of Experiment 2b would be reliable, and replicated the successful tracking of statistical information using a new sample of participants, still with the *us3* voice. As shown in Figure 6 (bottom), the average performance differed significantly from the chance level of 50%, ($M = 62.78$, $SD = 21.35$), Cohen's $d = 0.6$, $CI_{.95} = 54.81$, 70.75, $V = 320$, $p = 0.008$. As shown in Table 6, performance did not depend on the language condition, and was significantly better than in the pre-segmented condition ($p = .013$).

Taken together, these results thus suggest that Statistical Learning mechanisms predominantly operate in continuous sequences, but less so in pre-segmented sequences (see also Shukla et al., 2007, 2011). Such a result is compatible with the view that Statistical Learning is important for predictive processing, given that continuous sequences are more conducive for prediction. In contrast, it raises doubts as to whether participants can use Statistical Learning mechanisms to memorize words, given that they do not seem to be able

to do so in pre-segmented streams.

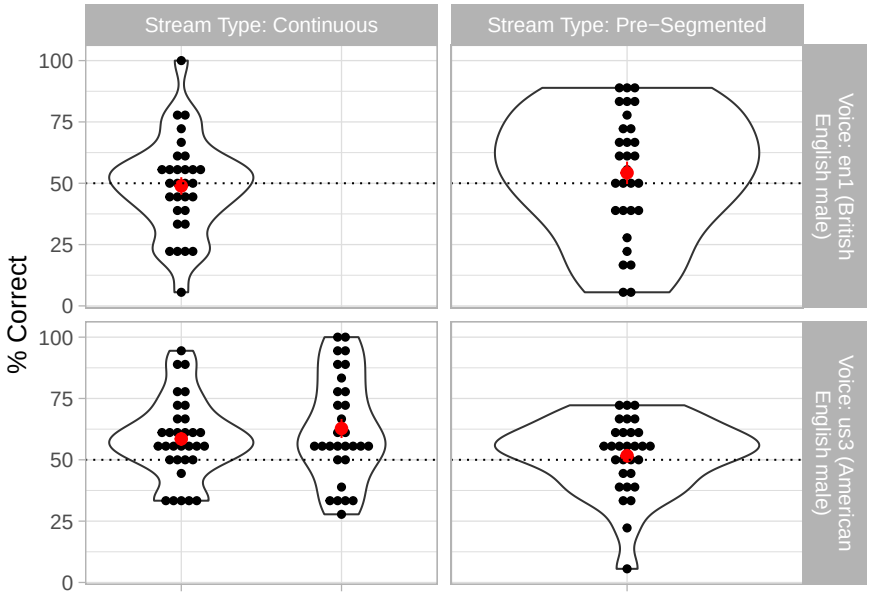

Figure 6. Results of Experiment 2. Each dot represents a participant. The central red dot is the sample mean; error bars represent standard errors from the mean. The results show the percentage of correct choices in the recognition test after familiarization with (left) a continuous familiarization stream or (right) a pre-segmented familiarization stream, with a British English voice (en1, top) or an American English voice (us3, bottom). The two continuous conditions with the American English voice are replications of one another.

3.3 Discussion

In Experiment 2, participants tracked statistical dependencies predominantly when they were embedded in a continuous speech stream, but not across pre-segmented chunk sequences. This finding does not contradict the results from the Experiment 1 above, where TPs were somewhat higher in the pre-segmented condition; after all, if participants faithfully recall familiarization items, the resulting TPs will be high as well.

This result is also consistent with earlier findings that Statistical Learning predominantly occurs within major prosodic groups, and, within these groups, predominantly at the edges of those groups (Shukla et al., 2007; Seidl & Johnson, 2008). We show that, with shorter and better separated groups, Statistical Learning can be abolished altogether. In line with results from conditioning experiments (Alberts & Gubernick, 1984; Garcia et al., 1974; Gubernick & Alberts, 1984; L. T. Martin & Alberts, 1979), Statistical Learning, and maybe associative learning in general, can thus be enhanced or suppressed depending on the learning situation. The enhanced Statistical Learning in continuous sequences is consistent with the view that Statistical Learning is important for predictive processing (Turk-Browne et al., 2010; Sherman & Turk-Browne, 2020), given that prediction is arguably more useful in lengthy chunks. It is also consistent with the view that Statistical Learning may be less important for memorizing words (or at least to break up utterances so that the underlying words can be memorized), especially given that, due to its prosodic organization, speech tends to be pre-segmented into smaller groups (Cutler et al., 1997; Nespor & Vogel, 1986; Shattuck-Hufnagel & Turk, 1996; Brentari et al., 2011; Endress & Hauser, 2010; Pilon, 1981; Christophe et al., 2001).

A possible alternative interpretation is that, in the continuous streams of

Experiment 2, repeated bisyllabic items pop out (and are thus remembered), while, in the pre-segmented streams, chunking cues (in the form of silences) prevent sub-chunks from popping out. However, if repeated bisyllabic items pop out in Experiment 2's continuous streams, repeated *trisyllabic* items (i.e., words) should pop out in Experiment 1 as well, and participants should be able to recall them as a result. As this prediction is falsified, a reasonable conclusion is that Statistical Learning does not make repeating elements pop out. Conversely, the availability of chunks might make Statistical Learning of within-chunk regularities more difficult, especially if chunks are memorized as whole units. This possibility would also confirm that Statistical Learning is separable from the (declarative) mechanisms involved in memorizing chunks.[4]

Further, while our trisyllabic items are relatively short, so are utterances in infant-directed speech. For example, infant-directed utterances have a typical duration of about 1 s (with some cross-language variability; see e.g., Fernald et al., 1989; Grieser & Kuhl, 1988), with a mean utterance length of about 4 (e.g., Snow, 1977; Smolak & Weinraub, 1983; see also A. Martin, Igarashi, Jincho, & Mazuka, 2016). As a result, if Statistical Learning is difficult in shorter utterances, the utility of Statistical Learning for language acquisition might be reduced.

This is not to say that Statistical Learning can never occur in pre-segmented units. While the available statistical information does not always improve performance when chunking information is available (e.g., Sohail &

[4] A further possible alternative interpretation of the difference between Experiments 1 and 2 is that the bisyllabic elements in Experiment 2 occurred in different contexts of other syllables. However, the words in Experiment 1 also occurred in different contexts, namely that of other words. As a result, if the availability of variable contexts were sufficient for the formation of declarative memories from continuous speech, such memories should be obtained in both Experiments 1 and 2.

Johnson, 2016), Shukla et al. (2007) showed that, when adults learners are exposed to 10 syllables chunks (defined by intonational contours), they have some sensitivity to statistical information within the chunks, though they might also use declarative memory mechanisms to remember sub-chunks (see also Endress & Bonatti, 2007; Endress & Mehler, 2009a for additional results suggesting that Statistical Learning is possible within chunks). However, Shukla et al. (2007) also found that participants predominantly retain information at chunk edges rather than at chunk medial positions. At minimum, it is thus an empirical question to what extent Statistical Learning is useful for word segmentation in the short utterances infants are faced with.

4 General Discussion

Taken together, Experiments 1 and 2 suggest that Statistical Learning and (declarative) memory might fulfill different computational functions in the process of word-segmentation. The combined results echo dissociations between associative learning and declarative memory (Cohen & Squire, 1980; Graf & Mandler, 1984; Finn et al., 2016; Knowlton et al., 1996; Poldrack et al., 2001; Squire, 1992), suggesting that the (cortical) declarative memory system might be independent of a (neostriatal) system for associative learning (Knowlton et al., 1996; Poldrack et al., 2001; Squire, 1992), though other authors propose that both types of memory involve the hippocampus (Sherman & Turk-Browne, 2020; Ellis et al., 2021). In line with earlier proposals (Turk-Browne et al., 2010; Sherman & Turk-Browne, 2020), we thus suggest that the computational function of associative learning might be distinct from that of (declarative) memory encoding, and that associative learning might be more important for predictive processing. The relative salience of these mechanisms might depend

on how useful and adaptive they are for the learning problem at hand.

These results also have implications for the more specific problem of word segmentation. If learners cannot use Statistical Learning to encode word candidates in (declarative) memory, they need to use other cues. Possible cues include using known words as delimiters for other words (Bortfeld, Morgan, Golinkoff, & Rathbun, 2005; Brent & Siskind, 2001; Mersad & Nazzi, 2012), attentional allocation to beginnings and ends of utterances (Monaghan & Christiansen, 2010; Seidl & Johnson, 2008; Shukla et al., 2007), legal sound sequences (McQueen, 1998) and universal aspects of prosody (Brentari et al., 2011; Christophe et al., 2001; Endress & Hauser, 2010; Pilon, 1981). Such cues might plausibly support declarative memories of words because they (but not transition-based associative information) are consistent with how linguistic sequences are encoded in declarative long-term memory, where linguistic sequences are encoded with reference to their first and their last element (Endress & Langus, 2017; Fischer-Baum et al., 2011; Miozzo et al., 2016).

This is no to say that Statistical Learning might play no implicit role in word learning even when it is not sufficient to produce memories that can be recalled. For example, and as mentioned above, associations among syllables might facilitate the establishment of declarative memories once suitable (and explicit) segmentation cues become available (Endress & Langus, 2017), and, once words are acquired, word processing is not immune to unconscious stimuli such as masked primes (e.g., Forster, 1998; Kouider & Dupoux, 2005). Statistical Learning might also facilitate word learning indirectly, for example through the acquisition of phonotactic constraint that might affect word learning in turn (e.g., Friederici & Wessels, 1993; Mattys, Jusczyk, Luce, & Morgan, 1999; McQueen, 1998). However, the extent to which Statistical Learning supports

such computations remains to be established. For example, the phonotactic regularities above can be learned by keeping track of material at utterance boundaries (Monaghan & Christiansen, 2010), and thus just using the type of cues we introduced in the pre-segmented conditions. As a result, we believe that it is an important topic for further research to determine the role Statistical Learning plays in word acquisition.

To the extent that Statistical Learning reflects implicit memory systems (e.g., Meulemans & van der Linden, 1997; Christiansen, 2018; but see Toro, Sinnett, & Soto-Faraco, 2005; Turk-Browne, Jungé, & Scholl, 2005), this suggestion mirrors earlier proposals that implicit and declarative memory systems might have different roles during language acquisition, with declarative memory systems supporting the acquisition of words and implicit memory system supporting the grammar-like regularities (Ullman, 2001; Pinker & Ullman, 2002). While we are agnostic about the extent to which Statistical Learning can support grammar acquisition, such results, together with the current ones, suggest that Statistical Learning and declarative memory might have separable functions, the former for predictive processing and the latter for remembering objects and episodes.

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Supplementary Online Materials

for Endress & de Seyssel: The specificity of sequential Statistical Learning: Statistical Learning accumulates predictive information from unstructured input but is dissociable from (declarative) memory

SOM1 Measures and column names in the supplementary data file for Experiment 1

Table S1
Analyses performed for the vocalizations

Column name in data file	Meaning
n.items	Number of recalled items
n.syll	Mean number of syllables of the recalled items
n.words	Number of recalled words
p.words	Proportion (among recalled items) of words
n.words.or.multiple	Number of recalled words or concatenation of words
p.words.or.multiple	Proportion (among recalled items) of words or concatenation of words
n.part.words	Number of recalled part-words
p.part.words	Proportion (among recalled items) of part-words
n.part.words.or.multiple	Number of recalled part-words or concatenation of part-words
p.part.words.or.multiple	Proportion (among recalled items) of part-words or concatenation of part-words
p.words.part.words	Proportion of words among (recalled) words and part-words. This is used for comparison to the recognition test.
p.words.part.words.or.multiple	Proportion of words among (recalled) words and part-words or concatenation thereof. This is used for comparison to the recognition test.
n.high.tp.chunk	Number of high TP chunks. High TP chunks are defined as two-syllabic chunk from a word
p.high.tp.chunk	Proprtion (among recalled items) of high TP chunks. High TP chunks are defined as two-syllabic chunk from a word
n.low.tp.chunk	Number of low TP chunks. Low TP chunks are defined as two-syllabic word transitions
p.low.tp.chunk	Proportion (among recalled items) of low TP chunks. Low TP chunks are defined as two-syllabic word transitions
p.high.tp.chunk.low.tp.chunk	Proportion of high-TP chunks among high and low-TP chunks. High TP Chunks are defined as two-syllabic chunks from words; low TP chunks are two-syllabic word transitions
average_fw_tp	Average (across recalled items) of average forward TPs among transitions in a given item.
average_fw_tp_d_actual_expected	Average (across recalled items) of the difference between the average ACTUAL forward TPs among transitions in a given item and the EXPECTED forward TP in that item, based on the items first element. See calculate.expected.tps.for.chunks for the calculations
average_bw_tp	Average (across recalled items) of average backward TPs among transitions in a given item.
p.correct.initial.syll	Proportion (among recalled items) that have a correct initial syllable.
p.correct.final.syll	Proportion (among recalled items) that have a correct final syllable.
p.correct.initial.or.final.syll	Proportion (among recalled items) that have a correct initial or final syllable.

SOM2 Additional results for Experiment 1

Table S2

Supplementary analyses pertaining to the productions as well as test against their chances levels in the recall phase of Experiments 1a and 1b. The p value in the rightmost column reflects a Wilcoxon test comparing the continuous and the pre-segmented conditions.

	Continuous	Segmented	p(Continuous vs. Segmented).
Number of words			
lab-based (Exp. 1a)	M= 0.308, SE= 0.139, p= 0.0719	M= 1.85, SE= 0.308, p= 0.00224	0.005
online (Exp. 1b)	M= 0.224, SE= 0.0791, p= 0.00482	M= 1.32, SE= 0.143, p= 7.32e-11	< 0.001
Proportion of words among productions			
lab-based (Exp. 1a)	M= 0.308, SE= 0.139, p= 0.0719	M= 1.85, SE= 0.308, p= 0.00224	0.005
online (Exp. 1b)	M= 0.224, SE= 0.0791, p= 0.00482	M= 1.32, SE= 0.143, p= 7.32e-11	< 0.001
Number of part-words			
lab-based (Exp. 1a)	M= 0.692, SE= 0.273, p= 0.031	M= 0, SE= 0, p= NaN	0.031
online (Exp. 1b)	M= 0.25, SE= 0.0657, p= 0.000717	M= 0, SE= 0, p= NaN	< 0.001
Proportion of part-words among productions			
lab-based (Exp. 1a)	M= 0.692, SE= 0.273, p= 0.031	M= 0, SE= 0, p= NaN	0.031
online (Exp. 1b)	M= 0.25, SE= 0.0657, p= 0.000717	M= 0, SE= 0, p= NaN	< 0.001
Actual vs. expected forward TPs			
lab-based (Exp. 1a)	M= -0.462, SE= 0.07, p= 0.000244	M= -0.315, SE= 0.0803, p= 0.00915	0.147
online (Exp. 1b)	M= -0.42, SE= 0.0329, p= 1.3e-12	M= -0.352, SE= 0.0365, p= 7.56e-11	0.120
Number of High-TP chunks			
lab-based (Exp. 1a)	M= 0.769, SE= 0.459, p= 0.181	M= 2.31, SE= 0.361, p= 0.00224	0.022
online (Exp. 1b)	M= 1.13, SE= 0.13, p= 5.35e-10	M= 1.62, SE= 0.147, p= 6.19e-12	0.014
Proportion of High-TP chunks among productions			
lab-based (Exp. 1a)	M= 0.104, SE= 0.0601, p= 0.181	M= 0.615, SE= 0.0999, p= 0.00241	0.003
online (Exp. 1b)	M= 0.279, SE= 0.0331, p= 1.08e-09	M= 0.516, SE= 0.0435, p= 8.27e-12	< 0.001
Number of Low-TP chunks			
lab-based (Exp. 1a)	M= 0.0769, SE= 0.0801, p= > .999	M= 0, SE= 0, p= NaN	> .999
online (Exp. 1b)	M= 0.355, SE= 0.0747, p= 2.41e-05	M= 0.0395, SE= 0.0226, p= 0.149	< 0.001
Number of Low-TP chunks among productions			
lab-based (Exp. 1a)	M= 0.011, SE= 0.0114, p= > .999	M= 0, SE= 0, p= NaN	> .999
online (Exp. 1b)	M= 0.0855, SE= 0.0198, p= 6.04e-05	M= 0.00846, SE= 0.00523, p= 0.181	< 0.001

* The expected TPs for items of at least 2 syllables starting on an initial syllable are 1, 1/3, 1, 1, 1/3, 1, 1, 1/3, ... The difference between the actual and the expected TP needs to be compared to zero, as the expected TP differs across items.

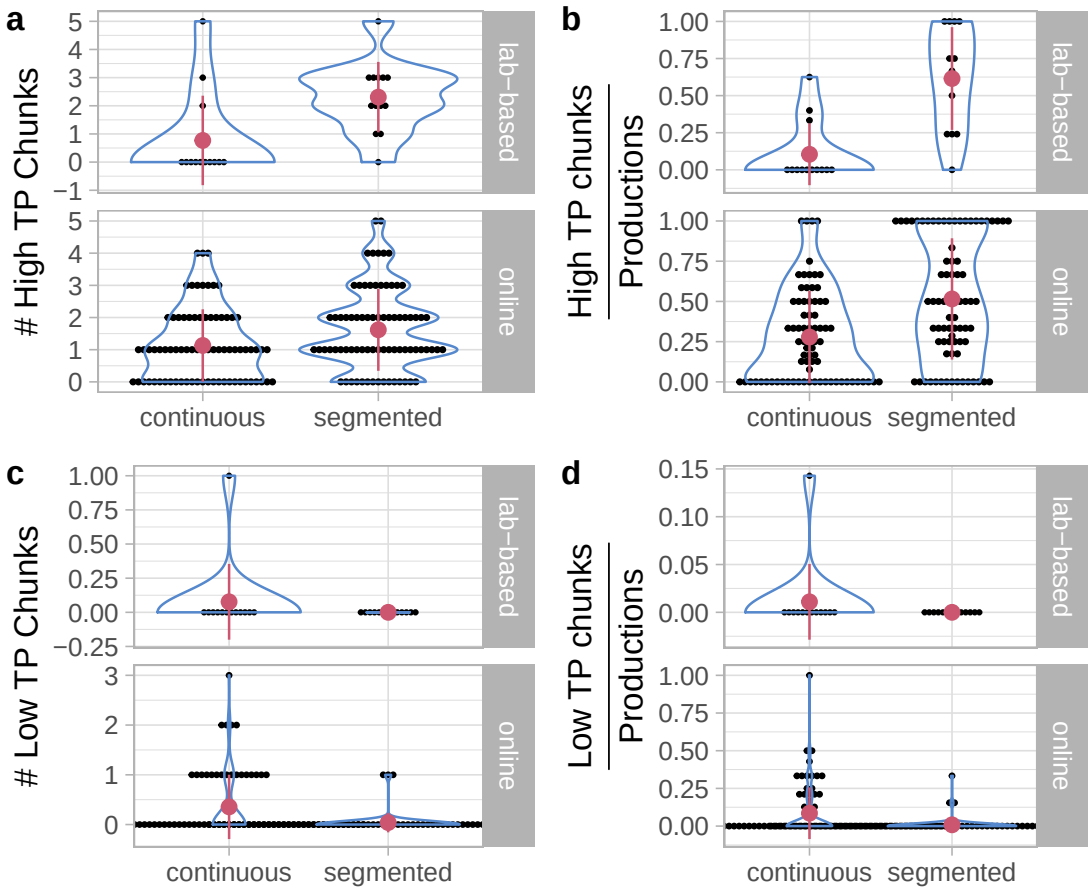

Figure S1. Plot of High and Low TP chunks.

SOM3 Fit of the number of participants producing words or part-words to a binomial distribution

We fit the data to two models, one where the learner successfully detected word-boundaries, and one where the learner successfully track TPs but initiates productions at a random position. We then calculate the likelihood of the data given these models.

According to the first model, the probability of producing words rather then part-words is $p^1_{\mathrm{W}} = 1$, and the probability of using part-words is $p^1_{\mathrm{PW}} = 1 - p^1_{\mathrm{W}} = 0$. According to the second model, the learner has one chance in three to initiate a production on a word-initial syllable. As a result, the probability of producing words is $p^2_{\mathrm{W}} = \frac{1}{3}$, and the probability of using part-words is $p^2_{\mathrm{PW}} = 1 - p^2_{\mathrm{W}} = \frac{2}{3}$.

Assuming that participants produce either words or part-words, the probability of N_{W} producing words and N_{PW} producing part-words is given by a binomial distribution. We can then use Bayes' theorem to calculate the model likelihood $P(\mathrm{model}|\mathrm{data}) = P(\mathrm{data}|\mathrm{model})\frac{P(\mathrm{model})}{P(\mathrm{data})}$. If both models are equally likely a priori, the likelihood ratio of the models given the data is the likelihood ratio of the data given the models:

$$
\begin{aligned}
\Lambda_{1,2} &= \frac{P(\text{model}_1|\text{data})}{P(\text{model}_2|\text{data})} = \frac{P(\text{data}|\text{model}_1)}{P(\text{data}|\text{model}_2)} \\
&= \frac{\begin{pmatrix} N_\text{W} + N_\text{PW} \\ N_\text{W} \end{pmatrix}}{\begin{pmatrix} N_\text{W} + N_\text{PW} \\ N_\text{W} \end{pmatrix}} \frac{1^{N_\text{W}} 0^{N_\text{PW}}}{\frac{1}{3}^{N_\text{W}} \frac{2}{3}^{N_\text{PW}}} \\
&= \begin{cases} 3^{N_\text{PW}} & N_\text{PW} = 0 \\ 0 & N_\text{PW} > 0 \end{cases}
\end{aligned}
$$

For $N_\text{PW} = 0$, the likelihood ratio in favor of the first model is 3^{N_PW}; $N_\text{PW} > 0$ the likelihood ratio in favor of the second model is infinite.

SOM4 Analyses of Experiment 2 after removing outliers

We repeat the analyses of Experiment 2 after removing outliers differing by more than 2.5 standard deviations from the mean in each condition ($N = 2$). As in the main analyses above, we first present the results for the British English (en1) voice and then those for the American English (us3) voice.

SOM4.1 Experiment 2a (British English voice)

Figure S2 shows the results for the pre-segmented familiarization. The average performance did not differ significantly from the chance level of 50%, ($M = 54.26$, $SD = 25.09$), $t(29) = 0.93$, $p = 0.36$, Cohen's $d = 0.17$, $CI_{.95} =$ 44.89, 63.63, ns, $V = 222$, $p = 0.242$. Likelihood ratio analysis favored the null hypothesis by a factor of 3.555 after correction with the Bayesian Information Criterion. Further, as shown in Table S3, performance did not depend on the language condition.

We next asked if, in line with previous research, they can track TPs units that are embedded into a *continuous* speech stream. That is, participants listened to the very same speech stream as in the pre-segmented condition, except that the stream was continuous.

Figure S2 shows that the average performance did not differ significantly from the chance level of 50%, ($M = 47.13$, $SD = 17.42$), $t(28) =$ -0.89, $p =$ 0.382, Cohen's $d = 0.16$, $CI_{.95} = 40.5$, 53.75, ns, $V = 140$, $p = 0.551$. Likelihood analyses revealed that the null hypothesis was 3.629 than the alternative hypothesis after a correction with the Bayesian Information Criterion. However, as shown in Table S3, performance was much better for Language 1 than for Language 2, presumably due to some click-like sounds the synthesizer produced for some stops and fricatives (notably /f/ and /g/). These sounds might have

prevented participants from using statistical learning. We thus decided to replicate the results with a different, American English voice.

SOM4.1.1 Experiment 2b (American English voice). Figure S2 shows the results for the pre-segmented condition with the American English (us3) voice. The average performance did not differ significantly from the chance level of 50%, ($M = 53.26$, $SD = 12.64$), $t(28) = 1.39$, $p = 0.176$, Cohen's $d = 0.26$, $CI_{.95} = 48.45, 58.07$, ns, $V = 216$, $p = 0.151$. Likelihood ratio analysis favored the null hypothesis by a factor of 2.058 after correction with the Bayesian Information Criterion. As shown in Table S3, performance did not depend on the language condition.

We next asked if, in line with previous research, they can track TPs units are embedded into a *continuous* speech stream. That is, participants listened to the very same speech stream as in the pre-segmented condition, except that the stream was continuous.

As shown in Figure S2, when the *us3* voice was used, the average performance differed significantly from the chance level of 50%, ($M = 58.51$, $SD = 16.21$), $t(31) = 2.97$, $p = 0.00573$, Cohen's $d = 0.52$, $CI_{.95} = 52.66, 64.35$, $V = 306.5$, $p = 0.0185$. As shown in Table S3, performance did not depend on the language condition, and was significantly better than in the pre-segmented condition.

Given the unexpected results with the *en1* voice above, we replicated the successful tracking of statistical information using a new sample of participants. As shown in Figure S2, the average performance differed significantly from the chance level of 50%, ($M = 62.78$, $SD = 21.35$), $t(29) = 3.28$, $p = 0.00272$, Cohen's $d = 0.6$, $CI_{.95} = 54.81, 70.75$, $V = 320$, $p = 0.00778$. As shown in Table S3, performance did not depend on the language condition, and was significantly

better than in the pre-segmented condition.

The results obtained after removing outliers are thus similar to those reported in the main text.

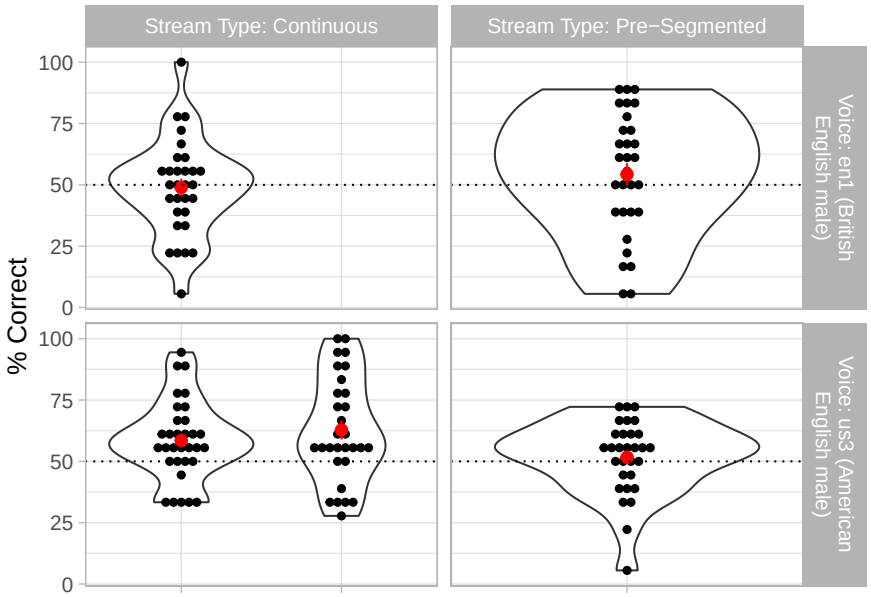

Figure S2. Results of Experiment 1 after outliers of more than 2.5 standard deviations from each condition mean were excluded. Each dot represents a participants. The central red dot is the sample mean; error bars represent standard errors from the mean. The results show the percentage of correct choices in the recognition test after familiarization with (left) continuous familiarization stream or (right) a pre-segmented familiarization stream, synthesized with a British English voice (top) or an American English voice (bottom). The two continuous conditions are replictions of one another.

Table S3

Performance differences across familiarization conditions in Experiment 2 after removal of outliers differing more thang 2.5 standard deviations from the mean. The differences were assessed using a generalized linear model for the trial-by-trial data, using participants, correct items and foils as random factors. Random factors were removed from the model when they did not contribute to the model likelihood.

		Log-odds			Odd ratios				
term	Voice	Estimate	SE	CI	Estimate	SE	CI	t	p
Pre-segmented familiarization, British English voice (Exp. 2a)									
language = L2	en1	-0.097	0.441	[-0.96, 0.767]	0.908	0.400	[0.383, 2.15]	-0.220	0.826
Continuous familiarization, British English voice (Exp. 2a)									
language = L2	en1	-0.842	0.221	[-1.28, -0.409]	0.431	0.095	[0.279, 0.665]	-3.807	0.000
Pre-segmented vs. continuous familiarization, British English voice (Exp. 2a)									
language = L2	en1	-0.903	0.369	[-1.63, -0.179]	0.406	0.150	[0.197, 0.836]	-2.446	0.014
stream type = segmented	en1	-0.090	0.347	[-0.77, 0.591]	0.914	0.317	[0.463, 1.81]	-0.258	0.796
language = L2 × stream type = segmented	en1	0.810	0.487	[-0.144, 1.76]	2.248	1.094	[0.866, 5.84]	1.664	0.096
Pre-segmented familiarization, American English voice (Exp. 2b)									
language = L2	us3	-0.048	0.654	[-1.33, 1.23]	0.953	0.624	[0.264, 3.44]	-0.074	0.941
Continuous familiarization (1), American English voice (Exp. 2b)									
language = L2	us3	-0.184	0.480	[-1.12, 0.757]	0.832	0.400	[0.325, 2.13]	-0.383	0.702
Continuous familiarization (2), American English voice (Exp. 2b)									
language = L2	us3	0.317	0.786	[-1.22, 1.86]	1.372	1.079	[0.294, 6.4]	0.403	0.687
Pre-segmented vs. continuous familiarization (1), American English voice (Exp. 2b)									
language = L2	us3	-0.102	0.551	[-1.18, 0.978]	0.903	0.497	[0.307, 2.66]	-0.185	0.853
stream type = segmented	us3	-0.243	0.167	[-0.571, 0.0843]	0.784	0.131	[0.565, 1.09]	-1.456	0.145
Pre-segmented vs. continuous familiarization (2), American English voice (Exp. 2b)									
language = L2	us3	0.115	0.652	[-1.16, 1.39]	1.122	0.732	[0.313, 4.03]	0.177	0.859
stream type = segmented	us3	-0.509	0.224	[-0.949, -0.0693]	0.601	0.135	[0.387, 0.933]	-2.269	0.023

SOM5 Pilot Experiment: Testing the use of chunk frequency

In a pilot experiment, we asked if participants could break up tri-syllabic items by using the chunk frequency of sub-chunks. The artificial languages were designed such that, in a trisyllabic item such as *ABC*, chunk frequency (and backwards TPs) favor in the initial *AB* chunk for half of the participants, and the final *BC* chunk for the other participants.

Across participants, we also varied the exposure to the languages, with 3, 15 or 30 repetitions per word, respectively.

SOM5.1 Methods

Table S4
Demographics of the final sample in the pilot experiment.

# Repetitions/word	*N*	Age (*M*)	Age (Range)
3	37	21.1	18-35
15	41	21.0	18-27
30	40	20.8	18-26

SOM5.1.1 Participants. Demographic information of the pilot experiment is given in Table S4. Participants were native speakers of Spanish and Catalan and were recruited from the Universitat Pompeu Fabra community.

SOM5.1.2 Stimuli. Stimuli transcriptions are given in Table S5. They were synthesized using the *es2* (Spanish male) voice of the mbrola (Dutoit et al., 1996) speech synthesized, using a segment duration of 225 ms and an fundamental frequency of 120 Hz.

SOM5.1.3 Apparatus. Participants were test individually in a quiet room. Stimuli were presented over headphones. Responses were collected from pre-marked keys on the keyboard. The experiment with 3 repetitions per word

(see below) were run using PsyScope X; the other experiments were run using Experyment (`https://www.expyriment.org/`).

SOM5.1.4 Familiarization. The design of the pilot experiment is shown in Table S5. The languages comprise trisyllabic items. All forward TPs were 0.5. However, in Language 1 the chunk composed of the first two syllables (e.g., *AB* in *ABC*) were twice as frequent as the chunk composed of the last two syllables (e.g., *BC* in *ABC*); the backward TPs were twice as high as well. Language 2 favored the word-final chunk. Participants were informed that they would listen to a sequence of Martian words, and then listened to a sequence of the eight words in 5 with an ISI of 1000 ms and 3, 15 or 30 repetitions per word. Due to programming error, the familiarization items for 15 and 30 repetitions per word were sampled with replacement.

Table S5
Design of the pilot experiment. (Left) Language structure. (Middle) Structure of test items. Correct items for Language 1 are foils for Language 2 and vice versa. (Right) Actual items in SAMPA format; dashes indicate syllable boundaries

Word structure for		Test item structure for		Actual words for	
Language 1	Language 2	Language 1	Language 2	Language 1	Language 2
ABC	ABC	AB	BC	ka-lu-mo	ka-lu-mo
DEF	DEF	DE	EF	ne-fi-To	ne-fi-To
ABF	DBC			ka-lu-To	ne-lu-mo
DEC	AEF			ne-fi-mo	ka-fi-To
AGJ	JBG			ka-do-ri	ri-lu-do
AGK	KBG			ka-do-tSo	tSo-lu-do
DHJ	JEH			ne-pu-ri	ri-fi-pu
DHK	KEH			ne-pu-tSo	tSo-fi-pu

SOM5.1.5 Test. Following this familiarization, participants were informed that they would hear new items, and had to decide which of them was in Martian. Following this, they heard pairs of two syllabic items with an ISI of 1000 ms. One was a word-initial chunk and one a word-final chunk.

The test items shown in Table 5 were combined into four test pairs, which were presented twice with different item orders. A new trial started 100 ms after a participant response.

SOM5.2 Results

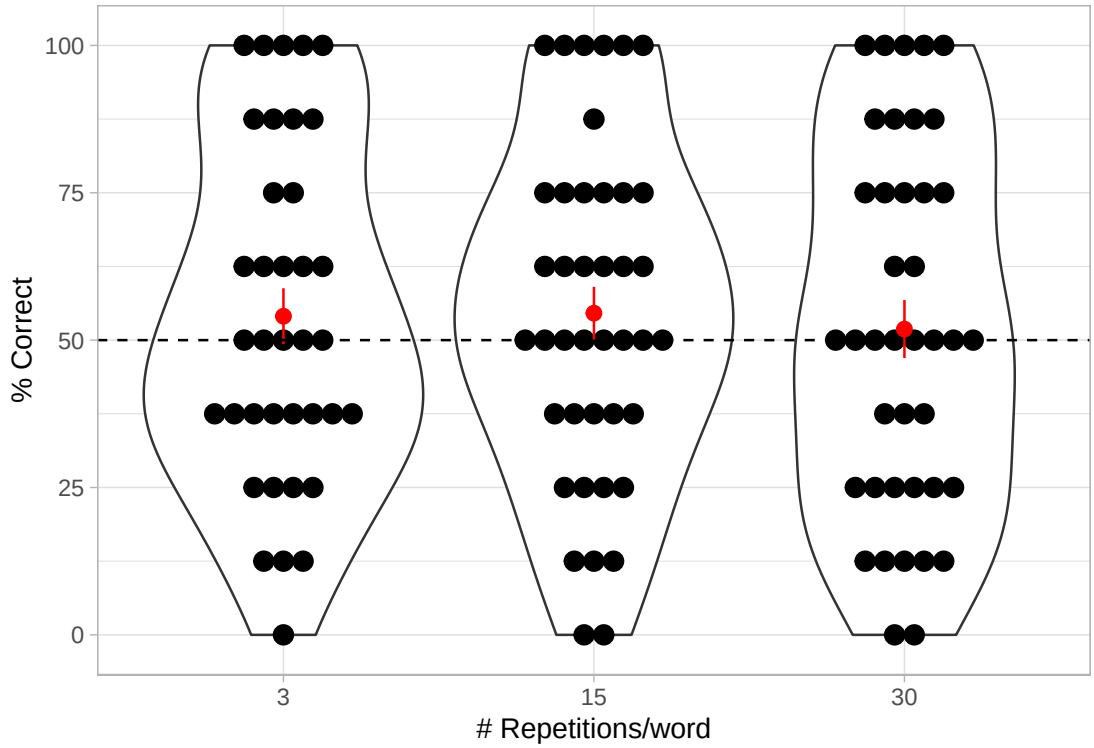

Figure S3. Results of the pilot experiment. Each dot represents a participants. The central red dot is the sample mean; error bars represent standard errors from the mean. The results show the percentage of correct choices in the recognition test after familiarization with (left) 3, (middle) 15 or (right) 30 repetitions per word.

As shown Table S6, a generalized linear model revealed that performance depended neither on the amount of familiarization nor on the familiarization language. As shown in Figure S3, a Wilcoxon test did not detect any deviation from the chance level of 50%, neither for all amounts of familiarization combined, M= 53.5, SE= 2.71, p= 0.182, nor for the individual familiarization

Table S6
Performance in the pilot experiment for different amounts of exposure. The differences were assessed using a generalized linear model for the trial-by-trial data, using participants as a random factor.

	Log-odds					Odds ratios				
term	Estimate	SE	CI	t	p	Estimate	SE	CI	t	p
language = L2	0.337	0.493	[-0.629, 1.3]	0.684	0.494	1.401	0.691	[0.533, 3.68]	0.684	0.494
number of repetitions/word	0.017	0.018	[-0.018, 0.0513]	0.942	0.346	1.017	0.018	[0.982, 1.05]	0.942	0.346
language = L2 × number of repetitions/word	-0.042	0.025	[-0.0916, 0.00698]	-1.682	0.093	0.959	0.024	[0.912, 1.01]	-1.682	0.093

conditions (3 repetitions per word: M= 54.1, SE= 4.81, p= 0.416; 15 repetitions per word: M= 54.6, SE= 4.52, p= 0.325; 30 repetitions per word: M= 51.9, SE= 4.98, p= 0.63). Following Glover and Dixon (2004), the null hypothesis was 4.696 times more likely than the alternative hypothesis after corrections with the Bayesian Information Criterion, and 1.217 more likely after correction with the Akaike Information Criterion.