Extracting Words in Homogeneous vs. Heterogeneous Speech Streams: Evidence from the Triplet Embedded Paradigm

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Trabalho efetuado sob a orientação da **Doutora Ana Paula Soares** e da **Doutora Helena Baldassarre**

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## STATEMENT OF INTEGRITY

I hereby declare having conducted this academic work with integrity. I confirm that I have not used plagiarism or any form of undue use of information or falsification of results along the process leading to its elaboration.

I further declare that I have fully acknowledged the Code of Ethical Conduct of the University of Minho.

(Dario Paiva)

Universidade do Minho, 6 de janeiro de 2022

Extração de Palavras em Streams Homogéneas vs. Heterogéneas: Evidência do Paradigma de Tripletos Embebidos


## Resumo

A aprendizagem estatística (*statistical learning*) é um mecanismo de extração de regularidades do ambiente sensorial, essencial para várias competências do ser humano, nomeadamente a aprendizagem de linguagem. O estudo deste mecanismo tem sido realizado sob condições que se distanciam, em alguns aspetos, da aprendizagem de línguas naturais, entre eles a heterogeneidade dos estímulos, em termos de previsibilidade, e a atenção dada aos estímulos. Neste estudo procuramos manipular estes dois fatores, numa tarefa típica de reconhecimento de tripletos com escolha forçada entre duas alternativas. Cada participante realizou a tarefa de aprendizagem sob condições implícitas e explícitas de aprendizagem de um dos seguintes tipos de *stream*: *Unmixed_high-TP*, composta por quatro tripletos com uma configuração de sílabas de alta probabilidade, *Unmixed_low-TP*, composta por quatro tripletos com uma configuração de sílabas de baixa probabilidade ou *Mixed*, composta por dois tripletos *high-TP* e dois *low-TP*. Os resultados demonstram que a aprendizagem não foi afetada pela aquisição de dois tipos de tripletos simultaneamente (*stream Mixed*), em contraste com as *streams* homogéneas. A análise das condições de instrução demonstrou uma vantagem de aprendizagem na tarefa explícita, em relação à tarefa implícita.



*Palavras-chave*: aprendizagem estatística, aprendizagem implícita, entropia

Extracting Words in Homogeneous vs. Heterogeneous Speech Streams: Evidence from the Triplet Embedded Paradigm


## Abstract

Statistical learning (SL) is a mechanism of extraction of regularities from the environment, assumed to be essential to various skills of humans, namely the acquisition of language. Studies in SL generally use experimental conditions which do not resemble, in some aspects, the learning of natural languages, among them, and starring in this study, the heterogeneity of stimuli predictability and the attention towards learning, given through instruction. In this study, we aim to manipulate these two factors in a typical triplet segmentation task, followed by a two-alternative forced choice task (2-AFC). Each participant performed the task under implicit and explicit learning conditions (not instructed towards learning or otherwise) of these types of streams: Unmixed_high-TP, composed of four triplets with high probability syllable composition (high-TP). Unmixed_low-TP composed of four triplets of low probability syllable composition (low-TP), or Mixed, composed of two high-TP triplets and two low-TP triplets. Results show that learning two types of triplet simultaneously was not affected negatively, comparing with homogeneous streams. The analysis of instruction conditions demonstrated an advantage of learning in the explicit task, in comparison with the implicit task.



*Keywords:* statistical learning, implicit learning, entropy

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# Introduction

Statistical learning (SL) is a mechanism by which one is capable of extracting regularities of events, present in one's surrounding environment (Conway & Christiansen, 2005; Saffran et al., 1996, 1997, 1999; Siegelman, Bogaerts, & Frost, 2017; Siegelman, Bogaerts, Christiansen, et al., 2017; Turk-Browne et al., 2005). It has been assumed as an essential mechanism supporting the learning of various skills (see Sherman et al., 2020 for a review) many of which relevant to language acquisition. One such skill is the segmentation of words in a continuous speech stream, since there are no pauses between them indicating where a word ends, and the next begins, as it occurs in print. Evidence from the use of the SL mechanism in words' segmentations comes firstly from Saffran et al. (1996), in a study with 8-month-old infants who were exposed to an auditory stream made of four three-syllable nonsense words (e.g., *tucida; bupepo; modego; bibaca*) presented in a pseudorandom order (the same "word" cannot be presented twice in a row). These "words" were presented for two minutes, as an auditory stream of syllables, without pauses between each other (e.g., *bupepotucidamodegobibaca…*). The only cue available allowing the segmentation of the speech stream into "words" was the statistical regularities embedded in the speech stream, known as transitional probabilities (TPs) and that can be defined as the probability of one segment (Y), as a syllable, to occur once another segment (X), another syllable, has already occurred [P(Y|X)]. TPs within "words" are usually of 1.0, meaning that, within a "word", a given syllable is always preceded by another syllable. Conversely, TPs across word boundaries are much lower, .33 in Saffran et al.'s (1996), indicating that a given "word" can be followed by any of the remaining "words" with the same level of probability. For example, in the "word" *bupepo,* the syllable *bu* was always followed by the syllable *pe;* therefore, the transitional probability (TP) of this event (hearing *pe* after *bu*) was 1.0. It was therefore hypothesized that a drop in syllable TPs provides a reliable cue for "word" segmentation, and it was precisely what Saffran et al. (1996) observed in the test phase that follows familiarization. In this phase, the infants were tested in a series of trials consisting of pairs of triplets: "words" presented before and new sequences of the syllables heard during the familiarization phase (foils) showing TPs of 0 (e.g., *tucida* vs. *tubago*-). Fixation time was used as an indicator of familiarization with stimuli. Longer fixation time for foils indicated that the infants observed them as novel stimuli, contrary to "words", thus indicating that the "words" they were exposed to in the familiarization phase were learned based on the extraction of the TPs. In a second experiment, they used, "part-words" as foils, which were a concatenation of the last syllable of a "word" with the first two syllables of another “word”. In this case, the “part-words” contained, each, a syllable pair that was presented in the familiarization phase (e.g., *tucida* vs. *tucigo*-). Despite the increased difficulty of the second experiment, infants were still able to correctly distinguish “words” from “part-words”. Since then, the *triplet embedded paradigm* became the standard paradigm to test SL, even with other stimuli and populations (Abla et al., 2008; Abla & Okanoya, 2009; Arciuli & Simpson, 2012; Batterink, Reber, & Paller, 2015; Batterink, Reber, Neville, et al., 2015; Bertels et al., 2014; Franco et al., 2011; Glicksohn & Cohen, 2013; Krogh et al., 2013; Saffran et al., 1997, 1999; Slone & Johnson, 2018; Soares et al., 2020; Soares, França, et al., 2022; Soares, Gutiérrez-Domínguez, Lages, et al., 2022; Soares, Gutiérrez-Domínguez, Oliveira, et al., 2022; Turk-Browne et al., 2008; Vasuki et al., 2017), even though using the post-learning two-alternative forced-choice (2-AFC) task to test SL. In this task, participants are asked to decide which stimulus of a pair (typically a “word” and a foil with TPs of 0) was presented before (Abla et al., 2008; Batterink, Reber, Neville, et al., 2015; Saffran et al., 1999; Siegelman et al., 2018; Soares et al., 2020; Soares, França, et al., 2022; Soares, Gutiérrez-Domínguez, Lages, et al., 2022; van Witteloostuijn et al., 2019, 2021). Above chance discriminations are taken as evidence of the extraction of the TPs during exposure.

Since this seminal study, SL has been shown to occur in various sensory modalities (e.g., auditory: Abla et al., 2008; Soares et al., 2020;  visual: Lavi-Rotbain & Arnon, 2021; Turk-Browne et al., 2005, 2008; tactile: Conway & Christiansen, 2005) and across different age groups (e.g., infants and adults; Abla et al., 2008; Saffran et al., 1996, 1997, 1999; Soares, Gutiérrez-Domínguez, Lages, et al., 2022). It is generally conceptualized as a type of learning that occurs incidentally and without awareness, since it occurs even when participants are not given explicit instructions about the regularities embedded in the input (Abla et al., 2008; Arciuli et al., 2014; Batterink, Reber, Neville, et al., 2015; Saffran et al., 1999). The fact that it is present in 8-month-old infants (Saffran et al., 1996) and that it occurs even when the subject is performing a distraction task, or not paying attention to the stimuli (e.g., Batterink & Paller, 2019; Saffran et al., 1997; Turk-Browne et al., 2005) further supports this view (see Batterink et al., 2015; Batterink & Paller, 2017; Bertels et al., 2014; Kim et al., 2009; Turk-Browne et al., 2009 for other works providing evidence for the implicit nature of SL using more direct measures of awareness). In spite of this, Batterink et al. (2015) argue that, while SL mostly resembles implicit learning, and, during a typical triplet segmentation task, produces implicit knowledge, of which the participant is unaware, explicit knowledge (knowledge that is accessible to awareness) can be formed alongside it. Using electrophysiological measures (EEG) during the exposure of an auditory triplet embedded task showed that the previous knowledge of the regularities embedded in speech streams can enhance the SL function, hence sustaining a view that both implicit and explicit representations can work together to allow an effective “word” segmentation. Research in the area of implicit learning shows contradictory results regarding the effect of instructing participants about regularities in stimuli prior to learning, with some reporting null effects (e.g., Arciuli et al., 2014; Dienes et al., 1991; Dulany et al., 1984) and some reporting positive effects (e.g., Howard & Ballas, 1980; Reber et al., 1980). Although SL occurs independently of the attention given to stimuli, most studies indicate that engaging participants’ conscious awareness toward learning, through instruction, is beneficial, although modulated by the complexity of stimuli, the specificity of instructions, and the presentation speed of stimuli (Arciuli et al., 2014; Siegelman et al., 2019).

Moreover, it is also worth noting that although most SL studies have used stimuli devoid of embedded unpredictability, in which, for example, a given syllable occurs in a single position of a single word (e.g., the syllable *tu* in *tucida; bupepo; modego; bibaca-*), learning under these conditions fails to resemble the unpredictability of natural languages, in which a given syllable can be present in multiple words (e.g., ‘bra’ in ‘brazen’, ‘brag’ or ‘braid’). A recent exception, by Soares et al. (2020), followed the classic paradigm from Saffran et al. (1996) while using triplets of different TPs to test whether the level of predictability had an impact on SL. The authors also tested the effect that providing previous knowledge of the regularities embedded in speech streams have on SL. To that purpose, previously to the exposure phase, participants were informed to the “words” embedded in the input, following Batterink et al. (2015) procedure. Each participant performed a triplet recognition task under implicit (no instructions about the stimuli) and explicit conditions (participants were told about the presence of an artificial language and which words were contained in it), in the respective order. Each task began with a familiarization phase, in which participants were exposed to a continuous stream (~7 minutes) of eight nonsense three-syllable “words”, four high-TP (TP = 1; *tucida, bupepo, modego, bibaca-*) and four low-TP (TP = 0.33, *dotige, tidomi, migedo, gemiti-*), presented through binaural headphones, in a pseudorandomized order, in which no syllables and no “words” were contiguous (neither *migedodotige* or *migedomigedo* were allowed to occur). Each “word” had a duration of 900ms. Low-TP “words”, such as “*dotige”* and “*tidomi”,* contained syllables that appeared in three different “words” (e.g.,“*do*” and “*ti”* appear in both these words) in different positions (which can be 1$^{st}$, 2$^{nd}$, or 3$^{rd}$ syllable). High-TP triplets, such as “*tucida*” and “*bupepo*”, contained syllables that were unique to each word and, therefore, to a single position. After familiarization, participants performed a 2-AFC task of 64 trials. In each, after being exposed to a "word" presented before and a foil, they had to decide, through a computerized task, which was most familiar. The foils were built with the same syllable set but combined in new sequences (TPs = 0). Rates of accuracy differing from chance (50%) were found for both high-TP and low-TP triplets in the SL task performed under implicit (57.1% and 56.8%, respectively) and explicit conditions (60.1% and 63.0%, respectively). Although performance was higher in the implicit than in the explicit SL task, differences failed to reach statistical significance (see however Soares, França, Gutiérrez-Domínguez, et al., 2022 and Soares, Gutiérrez-Domínguez, Lages, et al., 2022 for later works showing higher results in the SL task performed under explicit conditions). Moreover, it is worth noting that, although 2-AFC performance was above chance for both type of "words" in each of the tasks, they were nevertheless substantially below the ones observed in other studies. For instance, Abla et al. (2008) demonstrated accuracy rates averaging 74% in a triplet task where participants were uninstructed, and differentiated high (*M* = 90.2%), mid (*M* = 72.5%) and low learners (*M* = 58.6%). The accuracy rates found in Soares et al. (2020; 59%) are close to that of low learners. Other studies also show higher accuracy rates, closer to that of mid or high learners (Batterink, Reber, & Paller, 2015: 75%; Batterink & Paller, 2017: 89%; Cunillera et al., 2009: 67%; Sanders et al., 2009: 91%)

To explain the low rates of 2-AFC performance, Soares et al. (2020) pointed out that the higher complexity of the speech streams used, which contained not only a larger number of "words" (eight) than used in other SL studies (e.g., six: Abla et al., 2008; Batterink, Reber, & Paller, 2015; Saffran et al., 1999; Sanders et al., 2009; four: Batterink & Paller, 2017; Bertels et al., 2014; Cunillera et al., 2009; Franco et al., 2011; Saffran et al., 1996; Turk-Browne et al., 2008) that were repeated fewer times (60 instead of, usually, more than 100, as in most studies mentioned above), along with the use of different types of "words" (high-TP and low-TP) in the same stream, might have had detrimental effects on SL. Besides, the authors also claimed that the use of low-TP "words", that, by definition, contained syllables that occurred in other "words", made the syllables of the low-TP "words" occur three times more often in the stream than the syllables of the high-TP "words". This change in the distributional properties of the streams might make "words" harder to extract, which might contribute also to explaining the relatively low rates of 2-AFC performance observed by Soares et al. (2020).

The factors mentioned above can be unified and operationalized through the concept of entropy. In the context of SL, Siegelman et al. (2019) define entropy as a measure of how random/predictable the input is, given how much information each event carries given the event that preceded it. This is operationalized through Markov's entropy, in a formula that takes TPs of all possible transitions into account:

$$Markov\ entropy = -\sum_{i=1}^{n} p(i) \sum_{j=1}^{n} p(j|i) * log p(j|i)$$

This formula sums, for each transition *(i, j-),* the product of the distributional probability of *i* [p(*i* )], with the conditional probability of *i/j* [p(*j* | *i* )], and its logarithm [logp(*j* | *i* )]. We can use it to calculate entropy of a stream of triplets, inputting syllable pairs as transitions in the formula. Both a higher number of triplets and lower TPs increase entropy. A higher number of triplets increases entropy through the decrease of predictability in "word" boundaries, since each "word" can be followed by n-1 "words", or n-2 for low-TP "words". The TPs, inputted as conditional probabilities, of each syllable transition are represented by the second part of the formula, the product of the conditional probability of the transition with its logarithm. The higher the conditional probability, the lower the surprisal accounted for the syllable transition. This concept proves useful for better detailing the predictability of a set of stimuli in a stream, giving us a more complete and unified assessment of predictability. The factors suggesting a lack of accuracy rates in Soares et. al (2020) could be explained, in a unified manner, by the presentation of a highly entropic stream, evidenced through the use of more "words" than usual, learning low-TP words, and learning high-TP and low-TP words simultaneously, which reduce the level of predictability and introduce variations that might impact SL strongly. While streams with multiple "word" types do not change the calculation of entropy, by virtue of their heterogeneity of TPs, unpredictability from variation in distributional and transitional probabilities of the input might confound the strategies used by the learner during familiarization. Learning of low-TP "words" might rely mostly on the extraction of three-syllable combinations, given that the two-syllable pairs composing each "word" are less unique. For example, in the set *dotige|tidomi|migedo|gemiti* the syllable pair *doti* occurs in *dotige* and in the transition *migedotidomi.* Also, each syllable in this set can occur adjacent to any of the other three. Since syllable pairs within high-TP "words" are unique, the learner can more surely rely on syllable pairs to construct the whole "word". These two strategies might compete in a heterogeneous stream. These factors make statistical learning more difficult, which might be overshadowing potential differences between both types of "words" and between the implicit and explicit tasks.

The current study aimed to directly analyse which of the factors pointed out by Soares et al. (2020) explain the low level of 2-AFC performance in the SL tasks performed under implicit and explicit conditions. To that purpose, three types of streams were constructed, to which different groups of participants were exposed: two homogeneous streams made exclusively of high-TP or low-TP "words" and a heterogeneous stream made of half high- and half low-TP "words" as in the case of Soares et al. (2020). We decided to replicate this later condition because in the homogeneous high-TP and low-TP "words" we only used four "words" and we aimed to directly compare the 2-AFC performance obtained from them with another heterogeneous stream made of the same number of "words" (note that Soares et al., 2020 used eight "words"). As in Soares et al. (2020), participants in each group performed the SL task firstly without any instructions regarding the task or the stimuli (i.e., under implicit conditions) and then with the previous knowledge of them (i.e., under explicit conditions) to further analyse the effect that instructing participants has on accuracy under more controlled conditions. We calculated entropy values, measured in bits/element for each of the three types of stream presented in this study. Homogeneous high-TP: 0,16; heterogeneous: 0,26; homogeneous low-TP: 0,47. We expect that rates of accuracy for each type of stream to reflect their entropy levels. In this way, the heterogeneous type of stream will present accuracy rates in between the homogeneous high-TP and the homogeneous low-TP, and closer rates to homogeneous high-TP. We also expect higher rates of accuracy in the homogeneous high-TP, in comparison with homogeneous low-TP, supporting the hypothesis that higher TP "words" are easier to learn. In line with Soares et al. (2020) work we expect, in the Mixed stream, lower accuracies for the low-TP "words" than for the high-TP "words". Lastly, explicit instructions were expected to boost 2-AFC performance, particularly in the streams presenting higher levels of difficulty (i.e., the homogeneous low-TP streams and the heterogeneous streams).

## Method

### Participants

Fifty-nine undergraduate students from University of Minho (48 women, $M_{age} = 21.3$, $SD_{age} = 4.36$), were recruited for this experiment in exchange for academic credits. All were native speakers of European Portuguese, with normal hearing, normal or corrected-to-normal vision, and with no history of disabilities and/or neurological problems. Forty-six of these participants were right-handed, five left-handed, and nine were ambiguous-handed, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). Written informed consent was obtained from all participants. This study was approved by the local Ethics Committee (University of Minho, SECSH 028/2018).

### Stimuli

For the familiarization phase of this study, eight lists of four high-TP ($M_{TPs}$ = 1; *SD* = 0.03) and four low-TP ($M_{TPs}$ = 0.33; *SD* = 0.03) triplets were obtained from Soares et al. (2020). This set of words was built from two syllabaries, each with 16 syllables. High-TP words had syllables unique to each word and, thus, 12 syllables were necessary to construct four triplets. Low-TP words had syllables co-occurring three times across words, thus, a set of four low-TP words needed four syllables, each occurring three times. Given this, 16 syllables were necessary to build a list of four high-TP words and four low-TP words.

Furthermore, each syllable was rotated across lists so that it was present in all word types (high-TP and low-TP) and type of stream (both Unmixed and Mixed). These syllables were produced and recorded by a native speaker of European Portuguese with a duration of 300ms each. They were concatenated in Audacity® software (1999-2019) with an interval of 50ms between syllables, which summed to 1050ms per triplet. The computerized task played each triplet 115 times in a random order, with the limitation that the same nonsense word or syllable did not appear consecutively, summing up to 460 trials with an approximate duration of 8 minutes, with a superimposed click sound played over ~10% of syllables that would allow measuring participant's attention to the syllables through a target detection task. The click sound was used in all "words" and counterbalanced across syllable positions to prevent cueing that would facilitate word segmentation.

**Table 1**

*"Words" and Foils Used in the Experiment*

| Type of stream | "Word" / Foil | | | | | |
|---|---|---|---|---|---|---|
| | "Words" | | | Foils | | |
| **Unmixed_low-TP** | Do | Ti | Ge | Do | Ge | Ti |
| | Ti | Do | Mi | Ti | Mi | Do |
| | Mi | Ge | Do | Mi | Do | Ge |
| | Ge | Mi | Ti | Ge | Ti | Mi |
| **Unmixed_high-TP** | Tu | Ci | Da | Tu | Ba | Go |
| | Bu | Pe | Po | Bu | Ci | Ca |
| | Mo | De | Go | Mo | Pe | Da |
| | Bi | Ba | Ca | Bi | De | Po |
| **Mixed** | Do | Ti | Ge | Do | Ci | Mi |
| | Ti | Do | Mi | Bu | Do | Ge |
| | Tu | Ci | Da | Tu | Ti | Po |
| | Bu | Pe | Po | Ti | Pe | Da |

The foils used in the test phase were created using the same set of syllables as the corresponding "words" of each type of stream, as can be seen in Table 1. The syllables in foils were used with the same frequency and positions as the syllables in the "words", except with different syllable combinations. Participants were assigned to one of three types of stream: Unmixed_low-TP, in which four nonsense words are shown in the familiarization phase, which are all low-TP, and foils have TPs of .25, since the syllable pairs constituting foils have been presented as between-word syllable pairs in the familiarization phase (e.g., the syllable pair *ge-ti* was presented in the familiarization phase as a between "words" transition, and is present in the foil *dogeti*-); Unmixed high-TP, with four high-TP nonsense words and foils with TPs of 0, since all the syllable pairs constituting foils in this type of stream were not presented before; or Mixed, in which two nonsense words are high-TP and the other two are low-TP; and foils also have TPs of 0, as in Unmixed_high-TP. It must be noted that, while low-TP "words" in an Unmixed_low-TP stream present TPs of 0.33, the same "words" in a Mixed stream present TPs of 0.5. This is illustrated in Figure 1. Each participant was randomly assigned to a list from Syllabary A and a list from Syllabary B, one for the implicit task, and the other to the explicit task. For each participant, the lists used in the implicit and explicit conditions were from different syllabaries, which was done in order to minimize interference effects of the first list over the second list. The use of four lists of each type of "word" added syllable variation, and allowed the rotation of said syllables, eliminating the possibility that a learning effect would be due to the use of specific syllables or combinations of syllables.

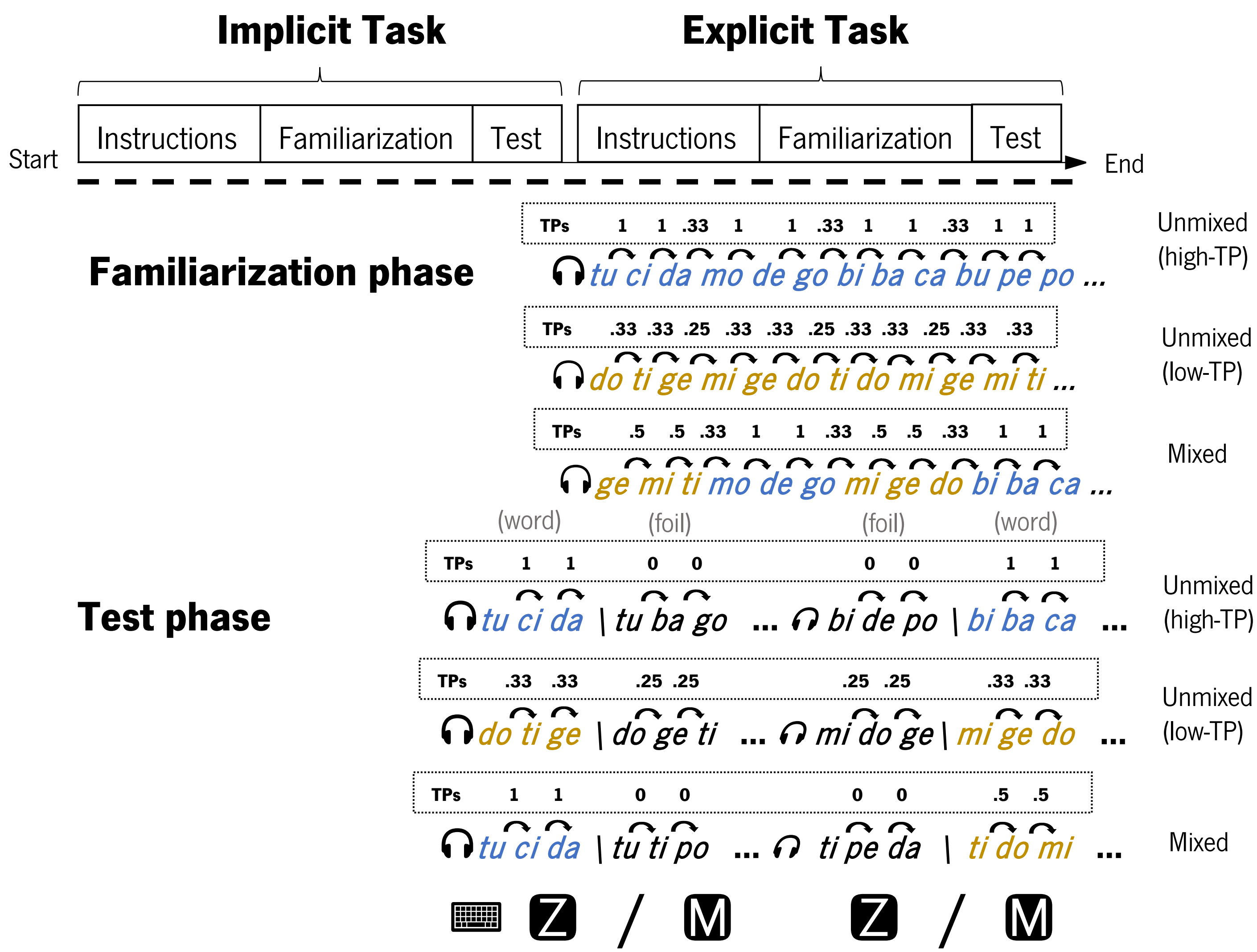
## Procedure

The structure of the procedure is illustrated in Figure 1. Participants began to fill the informed consent form and were then tested in an implicit and an explicit version of the task. Each of these tasks was composed of a familiarization phase, followed by a recognition phase. In the familiarization phase, participants were instructed to hear attentively a stream made of syllables, because occasionally a click sound would appear and their task would be to press the spacebar as fast and accurately as possible, which functioned as a cover task to assure that they would pay adequate attention to the auditory stream (see Soares, et al., 2020; or Soares et al., 2022 for a similar procedure).

Following the familiarization phase, participants performed a 2-AFC task. In this task, participants were asked to decide as accurately as possible which of two auditory presented stimuli (a "word" and a foil) resembled most the stream presented during the previous familiarization phase by pressing the Z button on the keyboard in case they considered the first stimulus resembled most the stream heard before, or the M button in case they considered it was the second instead. Participants were not told they would have a test phase, so as to ensure learning was incidental in the implicit task. The 2-AFC task entailed 16 trials for each of the tasks (implicit and explicit). Each trial consisted in the visual presentation of a fixation cross for 1,000ms followed by the auditory presentation of one of the two stimuli ("word" or foil), a 500ms interval of silence, and finally the remaining of the two stimuli. The next trial started after a response was registered or 10s had elapsed. In half of the trials, the "word" was presented first, and in the other half, the foil was presented first. It should be noted that, across the 16 trials, each of the four "words" was paired with each of the four foils.

**Figure 1**

*Structure of the Procedure*




After finishing the implicit task, the participant proceeded to the explicit version of the task, which followed a similar structure, this time with different instructions for the familiarization phase. Participants were instructed that they would be listening to an artificial sequence of "words", similar to the one presented before. The "words" they would be exposed to were presented one by one to the participant, during instructions, and prior to the familiarization phase. After this, as in the implicit task, participants performed a 2-AFC task after the familiarization phase. The whole procedure lasted approximately 25 minutes per participant

## Results

Table 2 presents the descriptive statistics (means and standard deviations – in brackets) of the number (percentage) of correct responses in each of the 2-AFC tasks (implicit and explicit) per type of stream (Unmixed_low-TP, Unmixed_high-TP and Mixed). All analyses run in this study used the R software (Bates et al., 2015) No participants' data were discarded due to the target detection task measuring attention, executed in the familiarization phase.

*T*-tests against the chance (50%) were run, in order to determine whether learning occurred for each type of stream, comparing accuracy against chance. These demonstrated above chance performance for all conditions: Unmixed_high-TP_Implicit: $t = 6.13$, $p < .001$; Unmixed_low-TP_Implicit: $t = 2.08$, $p = .038$; Mixed_Implicit: $t = 4.37$, $p < .001$; Unmixed_high-TP_Explicit: $t = 9.96$, $p < .001$; Unmixed_low-TP_Explicit: $t = 4.37$, $p < .001$; Mixed_Explicit: $t = 9.12$, $p < .001$). A linear mixed effects (lme4) analysis (Bates et al., 2015) with random intercepts and two repeated-measure factors, Type of stream (Unmixed_low-TP|Unmixed_high-TP| Mixed) and Task (implicit|explicit) as fixed factors (see Barr et al., 2013 and Matuschek et al., 2017) was run. For the resulting errors, we resorted to a generalized lme with logistic link function and binomial variance. The models were fit using the lme4 R library (Bates et al., 2015) and the

**Table 2**

*Means and Standard Deviation of Percentage of Correct Responses for Each Task of Each Type of Stream*

| Task | Type of stream | | |
|---|---|---|---|
| | Unmixed_high-TP | Unmixed_low-TP | Mixed |
| **Implicit** | 67.0 (47.1) | 55.9 (49.7) | 61.4 (48.8) |
| **Explicit** | 75.3 (43.2) | 62.2 (48.6) | 71.9 (45.0) |

**Table 3**

*Means and Standard Deviation of Percentage of Correct Responses for both "Word" Types in the Mixed Type of Stream*

| Task | "Word" type | |
|---|---|---|
| | High-TP | Low-TP |
| **Implicit** | 64.4 (47.9) | 58.3 (49.4) |
| **Explicit** | 74.8 (43.5) | 65.0 (47.7) |

lmerTest R library (Kuznetsova et al., 2017) in order to contrast simple effects with differences of least squares means. For *p*-values equal or below .05 in post hoc comparisons, the Hochberg method for adjustment was applied (see Benjamini & Hochberg, 1995, and Hochberg, 1988 for details). The lme analysis reveals an effect of task, $\chi2$ (2) = 15.54, $p < .001$ and type of stream, $\chi2$ (1) = 10.57, $p = .005$). The effect of task indicates that participants were more accurate in the 2-AFC task performed under explicit (69.8%) than under implicit conditions (61.3%). For the effect of type of stream, the post hoc comparisons revealed a significant difference between the Unmixed_low-TP and Unmixed_high-TP types of stream ($p = .003$) and a marginal difference between the Unmixed_low-TP and Mixed conditions ($p = .070$) regardless of the tasks. This indicates that learning was advantaged in learning high-TP words in comparison with low-TP words and that learning was similar for the Mixed and Unmixed_high-TP condition.

A second analysis was run, regarding the Mixed type of stream exclusively, in order to determine if there was an effect of word predictability in this type of stream. The means and standard deviations of correct responses for the Mixed condition are shown in Table 3. In this latter analysis, no effect of “word” type was found. A significant main effect of task, $\chi2$ (1) = 9.05, $p = .003$, was observed, indicating, as in the previous analysis, a positive effect of instructions on accuracy.

## Discussion

This study aimed to clarify how the type of stream impacts SL under different conditions of instruction (implicit vs. explicit). Furthermore we analyse whether the predictability of “words” and whether instructing participants impact learning. With this aim, we tested SL under three conditions which varied in stream heterogeneity of word predictability (Unmixed vs. Mixed) and word predictability (high-TP vs. low-TP): Unmixed_high-TP, containing four high-TP "words"; Unmixed_low-TP, containing four low-TP "words" and Mixed, containing two high-TP "words" and two low-TP "words", with all having a phase of incidental learning (implicit task) and a phase of intentional learning (explicit task). The comparison between types of stream was done between-subjects and the comparison for effects of instruction was done within-subjects.

The accuracy data of all participants, regarding the 2-AFC task, can be summarized as follows: (i) learning was advantaged for Mixed streams, in comparison with Unmixed_low-TP streams, with marginal significance. (ii) learning in the explicit tasks was advantaged in all conditions, in comparison with implicit tasks; (iii) the results of the Mixed analysis show no statistically significant difference between "word" types. (iv) learning of more predictable "words" was easier than less predictable "words".

We can identify in the present study some factors modulating entropy. High-TPs vs. low-TPs where higher TPs contribute to less entropy. The number of words of a stream, where smaller numbers contribute to a more predictable and less entropic stream. The heterogeneity of TPs in stream does not change its entropy, by virtue of being heterogenic, but introduces unpredictability of "word" composition that might confound SL strategies. We calculated entropy values, measured in bits/element for each of the three types of stream presented in this study. Unmixed_high-TP: 0,16; Mixed: 0,26; Unmixed_low-TP: 0,47. All the comparisons observed before indicate that accuracy could be predicted by the level of entropy that a stream entails, where lower levels of entropy facilitate learning and higher levels of entropy hamper learning.

Firstly, our study aimed to answer whether simultaneously learning "words" of two levels of predictability would be disadvantaged in comparison to learning only one type of "word", that is, if the heterogeneity of TPs in the stream affected learning. In this regard, the most plausible comparison would be between the Mixed and the Unmixed_high-TP streams given the similarity between their foils, whose syllable-pairs are not presented in the familiarization phase. Foils in the Unmixed_low-TP condition have TPs of .25, which means that syllable pairs constituting foils were presented in the familiarization phase, which could have further confounded distinguishing between low-TP "words" and low-TP foils in the test phase for this type of stream. Our results show a marginally significant difference in the Mixed vs. Unmixed_low-TP comparison and no significant difference between the Mixed vs. Unmixed_high-TP comparison, which indicates that learning of the Mixed condition wasn't impacted. The lack of differences in accuracy between high-TP and low-TP “words” in the Mixed condition further supports the hypothesis learning two types of “word” simultaneously does not impact SL.

Secondly, our data is ambiguous in relation to whether learning high-TP “words” is easier than learning low-TP “words”. Previous studies indicate that higher TPs facilitate SL (Bogaerts et al., 2016; Siegelman et al., 2018). In Soares et al. (2020) there was no behavioral evidence of this effect. The authors attributed this to the higher complexity of stimuli, reflected in (i) more words to be learned (ii) of two types of predictability (iii) in a shorter familiarization phase, in comparison with other studies. The reduction of entropy in our stimuli, through the reduction of words to be learned and introduction of streams with homogeneous “word” TPs, has brought forth results evidencing an impact of “word” predictability on learning. As such, this indicates that the comparisons in Soares et al. (2020) did not reach statistical significance possibly due to these factors increasing entropy, thus hampering learning and overshadowing potential observable differences across conditions. In our data, the difference found between both Unmixed conditions corroborates the hypothesis that learning of more predictable stimuli is advantaged. However, distinguishing between “words” and foils of the Unmixed_low-TP stream was harder, not only because of a difference in predictability of “words”, but also of foils, given the fact that, syllable pairs in foils of this condition were presented in the familiarization phase, in word boundaries, which was not the case for Unmixed_high-TP or Mixed streams. Accuracy rates from Soares et al. (2020: 59%) appear to differ from rates in the Mixed type of stream (67%). The stream from Soares et al. (2020) presents an entropy of 0,47, while the Mixed stream has an entropy of 0,26. This change in entropy, and in accuracy rates, can be attributed to the fewer number of “words”, and, low-TP “words” having TPs of 0.5 instead of 0.33. The fact that no behavioural difference was found between high-TP and low-TP “words”, in the Mixed stream, is apparently in accordance with the data from Soares et al. (2020). The common factor between these two streams is the presence of two types of “word”. It is possible that this heterogeneity of TPs is neutralizing differences between low-TP and high-TP “words”. The lack of differences between “word” types in the Mixed stream is likely be due to a small sample size of trials, which were halved in this analysis, thus limiting the statistical power of the comparison. Also, mean accuracy rates alone appear to indicate a difference between high-TP and low-TP “words” and a difference in learning between these two types of “words” would be in accordance with what previous studies indicate (Bogaerts et al., 2016; Siegelman et al., 2018; Soares et al., 2020; Soares, Gutiérrez-Domínguez, Lages, et al., 2022).

Lastly, our results indicate a positive effect of instruction on SL which is in line with most studies testing this effect (Arciuli et al., 2014; Batterink et al., 2015; Soares et al., 2020; Soares, França, Gutiérrez-Domínguez, et al., 2022; Soares, Gutiérrez-Domínguez, Lages, et al., 2022; Soares, Gutiérrez-Domínguez, Oliveira, et al., 2022). It is worth noting that instructions can vary on level of specificity. In this study, participants were told exactly which words they would hear in the familiarization phase, thus, engaging their awareness toward "looking for regularities" and "exactly what regularities to look for", instead of just informing participants about the presence of regularities, which could confound learning. Most studies agree that, if instructions are specific enough, learning is advantaged (Arciuli et al., 2014; Batterink, Reber, Neville, et al., 2015). We also might conclude that the absence of differences between implicit and explicit tasks in Soares et al. (2020) could be attributed to either the higher entropy of the stream presented, overshadowing differences between the two tasks, or the use of 64 test trials creating an effect of interference, where, throughout the test phase, participants implicitly learn the foils and progressively begin identifying them as "words", as suggests Soares et al. (2021).

Future studies should further explore the learning of heterogeneous streams, that more closely resemble natural languages thus increasing the ecological validity of SL studies. A comparison between heterogeneous vs. homogeneous streams could be more reliable while using entropy as a measure. For example, building heterogeneous and homogeneous streams with equal entropies and testing whether learning rates are similar. The results from all the variables manipulated in this study also support the hypothesis of entropy being a unifying concept in understanding SL in the future, and thus, we propose the testing of this concept in future studies.

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Universidade do Minho

SECSH

## Subcomissão de Ética para as Ciências Sociais e Humanas

Identificação do documento: SECSH 028/2018

Título do projeto: *Correlatos neurodesenvolvimentais dos mecanismos implícitos-explícitos de aprendizagem em crianças com Perturbação Específica de Linguagem: Evidência com potenciais evocados cerebrais*

Investigador(a) Responsável: Ana Paula de Carvalho Soares, Departamento de Psicologia Básica, Escola de Psicologia, Universidade do Minho

Outros Investigadores: Montserrat Comesaña, Centro de Investigação em Psicologia (CIPsi), Escola de Psicologia, Universidade do Minho; Marisa Lobo Lousada, Escola Superior de Saúde, Universidade de Aveiro; David Simões, Escola Superior de Tecnologia da Saúde do Porto, Instituto Politécnico do Porto; Ana Sucena, Escola Superior de Tecnologia da Saúde do Porto, Instituto Politécnico do Porto; Ana P. Patrícia, Faculdade de Psicologia, Universidade de Lisboa

## PARECER

A Subcomissão de Ética para as Ciências Sociais e Humanas (SECSH) analisou o processo relativo ao projeto intitulado *"Correlatos neurodesenvolvimentais dos mecanismos implícitos-explícitos de aprendizagem em crianças com Perturbação Específica de Linguagem: Evidência com potenciais evocados cerebrais".*

Os documentos apresentados revelam que o projeto obedece aos requisitos exigidos para as boas práticas na investigação com humanos, em conformidade com as normas nacionais e internacionais que regulam a investigação em Ciências Sociais e Humanas.

Face ao exposto, a SECSH nada tem a opor à realização do projeto.

Braga, 12 de junho de 2018.

O Presidente

Paulo Manuel Pinto Pereira Almeida Machado