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Statistical Learning of Second-Order Transitional Probabilities in Humans

Laura Lazartigues, Fabien Mathy, and Frédéric Lavigne
Université Côte d'Azur, CNRS



1 - Introduction

The ability to learn serial order and transitional probabilities between items processed in sequences is central to language acquisition and processing (acquisition of phonological forms, Mosse & Jarrod, 2008; vocabulary, Majerus, Poncelet, Greffe, & Van der Linden, 2006; extraction of words, Saffran, Newport, & Aslin, 1996; syntax, Kidd, 2012; reading, Perez, Majerus & Poncelet, 2012). The effects of first-order TPs are reported in sequence processing (probability of an item B given a single preceding item A, see Aslin, Saffran, & Newport, 1998; Endress, & Langus, 2017). However, processing of language as well as sequences of various types of stimuli involve second-order TPs that correspond to the probability of an item C given a combination of two preceding items A and B (see Fig. 1). Second-order TPs are known to be difficult to learn (see Gomez, 1997) but their effects remain poorly understood, particularly by taking into account the sequential order of the stimuli in the sequence.

The present study investigated the effects of the order of presentation of the stimuli in the statistical learning of second-order TPs. The exclusive-or (XOR) logic allowed to create a set of sequences in which first and second-order TPs were dissociated. Indeed, in the XOR logic all first-order TPs are equal to .5 and only the combination of the two first stimuli in a specific order can predict the last one (see Fig. 1). To test the learning of the order of presentation, a given stimulus could be fully predicted ($p=1$) if preceded by a combination of two specific stimuli and if they were presented in a specific order. For instance, the ABC and BAF sequences used the same A and B stimuli, but different orders led to different predictions (C or F).

Objectives

The present study aimed at better understanding the role of order of presentation in the learning and processing of second-order TP.

Our hypothesis was that participants can learn second-order TP depending on the combination of two stimuli and take into account the order of presentation.

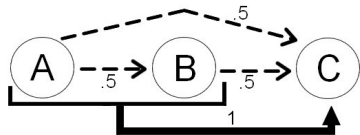


Figure 1
Structure of a sequence based on the XOR logic. All first-order TPs are equal to .5 and only the second-order TP is equal to 1. In this case, only the combination of the two first stimuli in a specific order allows to predict the last one.

2 - Method

Participants

37 participants, aged 24 on average.

Material

- 8 sequences were presented (Table 1), permuted in each block
- Stimuli were red dots on a 3*3 virtual grid (Fig. 2)
- Each trial began with a central white dot (Fig. 3)

Task

- Participants were asked to look at the dots when they appeared
- Saccade latencies were recorded as response times (RTs) with an eye tracker (EyeLink 1000)
- RTs were recorded between the two first items (Transition Time 1; TT1) and between the two last items (TT2)

Procedure

- A warm-up phase presented random three-item sequences and allowed to record the RTs of participants on every possible sequence. On this basis, 8 sequences with similar baseline transition times were selected for the learning phase for each participant (Example in Table 1).
- Learning phase : 7 blocks with the selected sequences were presented in a random order in each block (10 presentations of each sequence per block)
- Switch phase : In the last block, sequences were modified by changing the third stimulus, for instance if ABC and BAF were presented during the learning phase, ABF and BAC were presented in the switch phase (see Table 1)

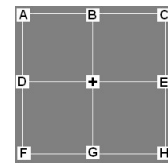


Figure 2
Virtual label of locations

Learning phase		Switch phase	
Order A	Order B	Order A	Order B
ABC	BAF	ABF	BAC
AEF	EAC	AEC	EAF
DBF	BDC	DBC	BDF
DEC	EDF	DEF	EDC

Table 1
Example of the manipulated pattern of sequences used in the learning phase and the switch phase

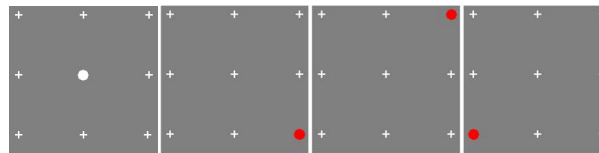


Figure 3
Example of trial. Sequence HCF

3 - Results and discussion

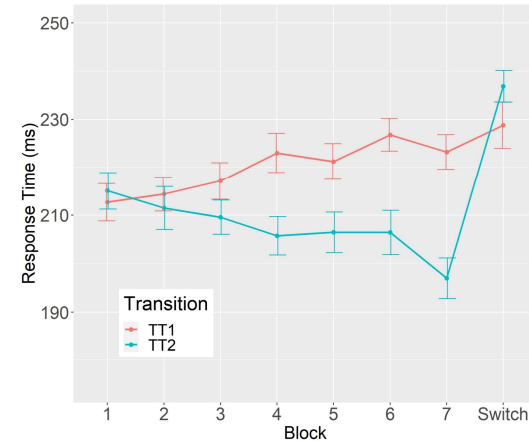


Figure 3
Evolution of response times (ms) for Transition Time 1 (TT1) and Transition Time 2 (TT2) during the learning phase (Block 1 to 7) and in the switch phase (Error bars correspond to +/- 1 standard errors).

Analyses showed that TT1 increased during the learning phase with no specific effect of the switch phase. This finding confirms that in the sequences used here the first stimulus alone cannot allow to predict the second stimulus. Conversely, results showed a significant decrease in RTs between the two last stimuli in the sequences (TT2) during the learning phase, and an increase in TT2 during the switch phase. The drop in performance in the switch phase suggested that the decrease in TT2 during the learning phase was not solely due to the training and that participants actually combine the first two stimuli and their order of presentation to predict the last one. These results suggest that participants can learn second-order TPs by taking into account their order of presentation.

However, alternative analyses focusing on each participant indicated that they learned **2.9 sequences among the eight in average** (a sequence was considered as learned when TT2 significantly increased between the last block of the learning phase and the switch phase). Moreover, when we focused on which sequences were learned, analyses indicated that **only 15 participants had learned at least one pair of ordered sequences** (for instance ABC and BAF). This result suggests that learning of second-order TP as a function of the specific order of presentation of the stimuli remains difficult.

Principal findings

- Participants can learn second-order TP as a function of the order of presentation of the stimuli to improve prediction in sequential processing (decrease in RTs of TT2).
- However, results also show that this learning remains difficult, with only a few sequences actually learned by the participants.

4 - Conclusion

The present experiment aimed at studying the statistical learning of second-order TPs as a function of serial order in a prediction task. The results indicated that participants could predict the last stimulus in a sequence based on the two previous stimuli (for instance A and B) and on the order in which these stimuli were presented (AB or BA), but it appeared to remain difficult. Indeed, only a few participants learned at least a pair of sequences manipulating the order of presentation (for instance ABC and BAF). This study provides an understanding of the difficulties that can emerge during the statistical learning of elementary sequences governed by complex statistical structures, in particular when the transitional probabilities involve second-order information. Perhaps efficient learning of this type of sequences would require additional learning trials.

To conclude, transitional probabilities, and in particular first-order transitional probabilities, are known to be involved in language acquisition, however our findings highlight the importance of also considering the effect of second-order transitional probabilities to better understand the mechanisms underlying language acquisition and processing.

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