Probabilistic sequence learning in decision making: ERP and fMRI studies

Project No.: FK 124412

Project Duration: 2017.09.01-2022.11.30.

Principal Investigator: Andrea Kóbor

Closing Report

1. Aim of the research project and the planned experiments

This research project aimed to investigate the neurocognitive processes underlying probabilistic sequence learning. This learning mechanism extracts and represents regularities of the environment and can be considered as a core element of human sequential decision making. By performing behavioral, ERP, and fMRI experiments, the project planned to track the trajectory of multiple learning processes in an unsupervised probabilistic sequence learning task (Experiment 1), to gain insight into the neuroanatomical networks supporting these processes (Experiment 2), and to track the learning of sequential regularities in a complex decision-making task with rewards (Experiment 3). With the help of the findings, an improved neurocognitive model of sequential decision making that involves probabilistic sequence learning processes could be delineated in the future.

2. Main conclusions

- The implicit and incidental acquisition of probabilistic regularities plays a critical role not only in simple unsupervised structure learning but also in reward-based learning.
- Probabilistic sequence learning is supported by predictive processes. These processes facilitate the dynamic update of mental representations to adapt to the continuously changing learning/decision environment.
- The robustness of the already acquired probabilistic knowledge and its resistance to interference have been confirmed in different learning/decision environments.
- Initial experience or practice has a significant influence on later behavior adaptation; however, this gradually weakens as new experience is accumulated. The length of this experience does not seem to modulate the speed of update.
- Probabilistic sequence learning could be considered as a domain-general adaptation device supporting the sensitivity to multiple levels of hierarchically organized temporal sequences. Statistical learning and rule-based learning are separable but simultaneous processes; the former is early and specific while the latter is more pervasive.

3. Project realization

We fulfilled the goals of the project and performed the planned experiments. We succeeded to deliver more publications than originally planned (see Publications section below): eight peer-reviewed research papers (instead of four), six poster presentations at international conferences (instead of four), and two oral presentations at Hungarian conferences. Two additional preprints and a doctoral dissertation were also written.

After finishing Experiment 1a that investigated the temporal parameters of probabilistic sequence learning, we performed two additional (originally unplanned) ERP experiments

(Experiments 1b, 1c) and a related behavioral experiment (Experiment 1d). These were built upon the findings and unanswered questions of Experiment 1a (see details in the Short summary section below).

Although we planned to run a three-session-long fMRI experiment (Experiment 2b) to track the different stages of probabilistic sequence learning from initial acquisition to consolidation, we reconsidered the original idea. We found a one-session-long fMRI experiment more viable because of laboratory capacities and limited human/financial resources. More importantly, based on the prior behavioral study (Experiment 2a), the focus of the fMRI study shifted to uncover how the neuroanatomical networks support the learning transfer between the predictable and unpredictable task blocks.

The design of Experiment 3 was also reconsidered based on the reanalysis of our earlier Balloon Analogue Risk Task (BART) behavioral data. We created a new design that was more suitable to reveal the hypothesized experimental effects in the ERPs. The reanalyzed behavioral data were also published during this project.

The project was finished 15 months after the originally planned end. A three-month-long extension in Augustus 2020 and an altogether one-year-long extension (3 + 9 months) in May 2021 have been approved. The delay was caused by several factors. First, data collection of Experiment 2b (fMRI experiment) was not possible for three months because of the COVID-19 pandemic and the related lockdown (reason for the first extension). Second, an unexpected personnel change occurred: Zsófia Klára Kardos was not able to work on Experiment 3 because of switching to a different field. Third, elaborating the experimental design of Experiment 3, revisions of manuscripts, and fMRI data collection and analysis took significantly more time than expected (reasons for the second extension).

4. Short summary of the results

4.1 What are the temporal parameters of probabilistic sequence learning?

4.1.1 Experiment 1a

We investigated whether two prominent learning processes – statistical learning and rule-based learning – can be distinguished at the level of neurocognitive correlates within the same experimental setting. Healthy young adults (N = 40) performed the explicitly cued version of the Alternating Serial Reaction Time (ASRT) task while RTs and ERPs were measured time-locked to the onset of the stimuli. In this task version, the repeating regularity was marked by different stimuli for sequence and random elements. According to the results, both RT and N2 effects reflected the rapid acquisition of statistical regularities. At the same time, these effects reflected the gradual learning of rules (sequential structures). The amplitude changes of the P3 reflected only gradual rule-based learning. These results altogether indicate that statistical learning and rule-based learning develop differently at the level of both ERPs and overt responses (*Kóbor et al., 2018, Biological Psychology*)

These data were reanalyzed with the application of a temporal EEG signal decomposition approach in combination with source localization analyses. Based on the decomposed N2 and P3 data, statistical learning and rule-based learning are separable but simultaneous processes that likely build upon each other. Moreover, while the right inferior frontal cortex (BA44) is shown to be implicated in statistical learning, rule-based learning is associated with the prefrontal gyrus (BA6). In sum, these results strengthen and widen our previous findings (*Takács et al., 2021, Human Brain Mapping*).

Furthermore, in this experiment, the response-locked ERPs were also analyzed. This allowed us to investigate error processing during the online retrieval of probabilistic sequence knowledge. Based on the results, we propose that automatic error detection and conscious error evaluation are not sensitive to rule-based (sequence) learning and retrieval. (*Horváth et al., 2021, Journal of Psychophysiology*).

4.1.2 Experiment 1b

Although Experiment 1a suggested that multiple probability distributions could be extracted from the same information stream, it remained unclear whether ERPs were sensitive to different probabilistic regularities without providing explicit information on the structure of the stimuli. Therefore, in Experiment 1b, the ASRT task was completed in a fully implicit experimental setting, where the repeating regularity was perceptually unsignaled ($N = 32$). RT and (stimulus- and response-locked) P3 effects suggested that sensitivity to the sequential regularity can be supported by the initial sensitivity to the transitional probabilities. Consequently, stimulus-response contingencies on the probabilistic regularities are implicitly mapped and constantly revised *(Kóbor et al., 2019, Memory & Cognition).*

4.1.3 Experiment 1c

As Experiment 1b highlighted the role of predictive processes during implicit memory formation, the question has emerged whether the anticipation of the upcoming stimulus and the preparation of the corresponding response could be reflected at the level of slow cortical potentials. We investigated this question in another ERP study using an implicitly cued ASRT task version. In this version, target stimuli were presented according to the probabilistic sequence and were preceded by warning cues unspecific to the predictability of the targets ($N = 36$). Results showed enhanced contingent negative variation (CNV) amplitude during response preparation but attenuated P3 amplitude during response execution for the unpredictable events as compared with the predictable ones. We propose that, during the preparatory phase of processing, more resources are needed to maintain the stimulus-response contingencies appropriate for the unpredictable events. This pattern of results possibly emerges due to the implicit and incidental acquisition of probabilistic regularities through the formation of internal models (*Kóbor et al., 2021, Neuropsychologia*).

4.1.4 Experiment 1d

Furthermore, based on these ERP results and motivated by a thorough literature review on conflict adaptation, we asked how the manipulation of executive control processes influence probabilistic sequence learning. In a behavioral experiment, participants completed an implicit ASRT task combined with the Eriksen flanker paradigm ($N = 36$). Particularly, flanker stimuli were presented alongside the central target stimuli that followed a probabilistic sequence. Both RTs and accuracy were influenced by the probability as well as the flanker property of trials in an additive manner. This indicates that probabilistic sequence learning and executive control processes operate independently when they are simultaneously involved in the task. However, investigation of the congruency sequence effect revealed a hampering effect between these processes. When a task event was predictable based on probabilistic sequence learning and previous trial incongruency induced conflict adaptation processes, a maladaptive overshoot and impaired performance was observed, at least when measured by RTs (*Horváth et al., 2021*

ESCAN – poster presentation, see the poster on OSF; *Horváth et al., 2022, Doctoral dissertation; Horváth et al., in preparation*).

4.2 Which neuroanatomical networks support probabilistic sequence learning?

4.2.1 Experiment 2a (v1, v2)

As part of designing the fMRI experiment (Experiment 2b), two behavioral experiments (Experiment 2a v1, v2) were conducted. In these ASRT task versions, two types of blocks were used. While the distribution of probabilistic regularities was predictable (biased) in one block type, it was unpredictable (equally probable) in the other. In the first experiment (Experiment 2a v1), the two block types alternated with one another. Participants ($N = 23$) were unaware of the presence of probabilistic regularities and of their changing distribution across the subsequent task blocks. Based on the RT results, unexpectedly, probabilistic regularities were processed similarly in both the predictable and unpredictable blocks. However, participants acquired less probabilistic knowledge in the unpredictable than in the predictable blocks. This raised the possibility of a cognitive transfer effect between the different block types.

Therefore, to directly test this transfer effect, a second experiment was conducted (Experiment 2a v2). In this experiment, while one group of participants ($n = 25$) completed the predictable blocks in the first task half and the unpredictable blocks in the second task half, the other group ($n = 25$) performed the opposite, starting with the unpredictable half. According to the results, implicit prior knowledge of the predictable structure was carried over (“transferred”) to the processing of unpredictable stimuli. This implied that, due to the persistency of the acquired representations, unpredictable stimuli were automatically processed according to these prior representations. After extended exposure to the unpredictable blocks, this robust knowledge was updated, but this required a longer stretch of time than initial learning (*Kóbor et al., Cognition, 2020*).

4.2.2 Experiment 2b

This fMRI experiment investigated how the brain encodes the distribution of probabilistic regularities if these regularities change continuously. The same alternating block design was used as in Experiment 2a v1. We collected fMRI data of 40 participants and could retain a sample of 32 participants for further analysis. RT results were in line with those found in the behavioral experiment: Although the actual predictable structure was lacking, unpredictable stimuli were still processed according to the acquired representations of the predictable patterns. Whole-brain random-effects analyses showed increased activity in the early visual cortex and decreased activity in the precuneus for the predictable as compared with the unpredictable blocks. Therefore, the actual predictability of probabilistic regularities was likely to be represented already at the early stages of visual cortical processing. However, decreased precuneus activity suggested that these representations were imperfectly updated to track the multiple shifts in predictability throughout the task. The results also highlight that the processing of probabilistic regularities in a changing environment could be habitual (*Kóbor et al., 2022, PsyArXiv preprint; Kóbor et al., 2021, ESCAN – poster presentation*).

4.3 What are the temporal parameters of probabilistic sequence learning during sequential decision making that involves risk taking?

4.3.1 Behavioral experiments

As part of designing Experiment 3, we reanalyzed two BART behavioral datasets collected in an earlier project. We followed different analytic approaches and theoretical considerations. In these earlier experiments, we manipulated the probabilistic regularities underlying balloon bursts (i.e., outcome probabilities) in several ways. We investigated whether participants could implicitly acquire the dynamically changing hidden structure of this risky decision-making task and adjust their behavior accordingly.

The first study investigated how recent outcomes attenuate the lasting effect of initial experience on risky decisions. Results confirmed that the combination of both primacy and recency effects contributes to experience-based risky decision making. Moreover, it was revealed that extended early experience does not induce more profound primacy effect than brief early experience. Therefore, while choice behavior remains risk averse after early negative events, this attenuates with the accumulation of new experiences on outcome probabilities (*Kóbor et al., 2021, Scientific Reports*).

The second study investigated whether sensitivity to differently structured outcome probabilities develops and remains persistent if outcomes probabilities unexpectedly change. In this variant of the BART, outcomes were predictable in the first and final task phases and unpredictable in the middle phase. The regularity underlying the predictable outcomes differed across the deterministic, probabilistic, and hybrid experimental conditions. Sensitivity to both the deterministic and hybrid regularities emerged and influenced risk taking. Unpredictable outcomes of the middle phase did not deteriorate the acquired sensitivity to these regularities. Therefore, expecting the reappearance of the initially experienced sequential patterns and the robustness of representations might serve adaptation to the changing decision environment (*Kóbor et al., 2021, PsyArXiv preprint*).

We also had the chance to collaborate on a related BART project investigating whether adolescents were more risk-prone when facing a novel and uncertain risky situation. Participants in all age groups (from 7 to 30 years) performed the BART and were able to adjust their learning processes to the probabilistic environment. Surprisingly, no age-related changes in risk-taking measures were found. These findings prompted important methodological considerations about the BART and highlighted the modulatory role of prior experience, which was also considered in Experiment 3 (*Éltető et al., 2019, Cognitive Development*).

4.3.2 Experiment 3

This ERP experiment investigated the temporal parameters of processing unexpected changes in outcome probabilities during uncertain decision making. The applied variant of the BART consisted of baseline, lucky, and unlucky phases. Due to different burst probabilities, balloon bursts occurred, on average, at medium (baseline), large (lucky), or small (unlucky) balloon sizes. We randomly assigned participants to two groups (25 to each). Both groups started with the baseline phase. The order of the two manipulation phases varied between the Lucky-first and Unlucky-first groups. ERPs were measured time-locked to the successfully inflated balloon stimuli (i.e., to each reward/risk step). Amplitude modulations of the reward positivity and late P3 components reflected sensitivity to the increasing risk of balloon burst, irrespective of group assignment. Thus, reward expectations might have been implicitly and automatically adjusted to changes in outcome probabilities. However, amplitude changes also revealed that early negative (Unlucky-first group) and mostly positive (Lucky-first group) experience modulate the processing and elaboration of high-risk and unexpected reward (*Kóbor et al., 2022 ESCOP – poster presentation, see the poster on OSF*). Further analyses (time-frequency analysis, computational modeling) are planned to better understand how the expectations are updated.

5. Publications related to the research project

5.1 Published papers

1. Takács, Á., **Kóbor, A.**, Kardos, Z., Janacsek, K., Horváth, K., Beste, C., & Nemeth, D. (2021). Neurophysiological and functional neuroanatomical coding of statistical and deterministic rule information during sequence learning. *Human Brain Mapping, 42*(10), 3182-3201.
2. **Kóbor, A.**, Kardos, Z., Takács, Á., Éltető, N., Janacsek, K., Tóth-Fáber, E., Csépe, V., & Nemeth, D. (2021). Adaptation to recent outcomes attenuates the lasting effect of initial experience on risky decisions. *Scientific Reports, 11*, 10132.
3. **Kóbor, A.**, Kardos, Z., Horváth, K., Janacsek, K., Takács, Á., Csépe, V., & Nemeth, D. (2021). Implicit anticipation of probabilistic regularities: Larger CNV emerges for unpredictable events. *Neuropsychologia, 156*, 107826.
4. Horváth, K., Kardos, Z., Takács, Á., Csépe, V., Nemeth, D., Janacsek, K., & **Kóbor, A.** (2021). Error processing during the online retrieval of probabilistic sequence knowledge. *Journal of Psychophysiology, 35*(2), 61-75.
5. **Kóbor, A.**, Horváth, K., Kardos, Z., Nemeth, D., & Janacsek, K. (2020). Perceiving structure in unstructured stimuli: Implicitly acquired prior knowledge impacts the processing of unpredictable transitional probabilities. *Cognition, 205*, 104413.
6. **Kóbor, A.**, Horváth, K., Kardos, Z., Takács, Á., Janacsek, K., Csépe, V., & Nemeth, D. (2019). Tracking the implicit acquisition of nonadjacent transitional probabilities by ERPs. *Memory & Cognition, 47*(8), 1546-1566.
7. Éltető, N., Janacsek, K., **Kóbor, A.**, Takács, Á., Tóth-Fáber, E., & Németh, D. (2019). Do adolescents take more risks? Not when facing a novel uncertain situation. *Cognitive Development, 50*, 105-117.
8. **Kóbor, A.**, Takács, Á., Kardos, Z., Janacsek, K., Horváth, K., Csépe, V., & Nemeth, D. (2018). ERPs differentiate the sensitivity to statistical probabilities and the learning of sequential structures during procedural learning. *Biological Psychology, 135*, 180-193.

5.2 Preprints

1. **Kóbor, A.**, Janacsek, K., Hermann, P., Zavecz, Z., Varga, V., Csépe, V., Vidnyánszky, Z., Kovács, G., & Nemeth, D. (2022). Predictability-dependent encoding of statistical regularities in the early visual cortex. *PsyArXiv*. https://psyarxiv.com/axq49
   The revised manuscript is going to be resubmitted in 2023.
2. **Kóbor, A.**, Tóth-Fáber, E., Kardos, Z., Takács, Á., Éltető, N., Janacsek, K., Csépe, V., & Nemeth, D. (2021). Deterministic and probabilistic regularities underlying risky choices are acquired in a changing decision context. *PsyArXiv*. https://psyarxiv.com/xwgk2
   The third round of revision is going to be submitted to Scientific Reports by the end of 2022.

5.3 Manuscripts in preparation

1. Horváth, K., Kardos, Z., Takács, Á., Nemeth, D., Janacsek, K., & **Kóbor, A.** Manipulation of inhibitory control does not influence procedural learning. *In preparation*.

5.4 Doctoral dissertations

1. Horváth, K. (2022). The interplay between the procedural memory and executive control systems in behaviour adaptation. Eötvös Loránd University. 10.15476/ELTE.2022.265.
   The dissertation includes the papers of Horváth et al., 2021, Journal of Psychophysiology; Kóbor et al., 2020, Cognition; and Horváth et al., in preparation. It successfully passed the in-house defense in October and the official defense is foreseen for January 2023.

5.5 Conference presentations

1. Horváth K., Kardos Zs., Takács Á., Janacsek K., Németh D., **Kóbor A.** (2019). A procedurális tanulás EEG korrelátumai. *A Magyar Pszichológiai Társaság XXVIII. Országos Tudományos Nagygyűlésén elhangzott szimpózium előadás*, Debrecen.
2. Horváth K., Kardos Zs., Takács Á., Janacsek K., Németh D., **Kóbor A.** (2018). Hibamonitorozás explicit probabilisztikus szekvenciatanulásban. *A Magyar Pszichológiai Társaság XXVII. Országos Tudományos Nagygyűlésén elhangzott szimpózium előadás*, Budapest.

5.6 Conference posters

1. **Kóbor, A.**, Tóth-Fáber, E., Éltető, N., Kardos, Z., Bárány, D., & Nemeth, D. (2022). Sensitivity to unexpected uncertainty is reflected by ERPs during risky decisions. *22nd conference of the European Society for Cognitive Psychology (ESCoP 2022)*, Lille. *The poster can be downloaded from* https://osf.io/angbr
2. **Kóbor, A.**, Janacsek, K., Zavecz, Z., Hermann, P., Varga, V., Vidnyánszky, Z., Kovács, G., & Nemeth, D. (2021). Implicit differentiation of structured and unstructured statistical regularities: fMRI evidence. *5th Conference of the European Society for Cognitive and Affective Neuroscience*, Budapest (online).
3. Horváth, K., Kardos, Z., Takács, Á., Janacsek, K., Nemeth, D., & **Kóbor, A.** (2021). Manipulation of cognitive control does not influence statistical learning: Evidence from a probabilistic sequence learning task combined with the Eriksen flanker paradigm. *5th Conference of the European Society for Cognitive and Affective Neuroscience*, Budapest (online). *The poster can be downloaded from* https://osf.io/hskjp
4. **Kóbor, A.**, Horváth, K., Kardos, Z., Zavecz, Z., German, B., Janacsek, K., & Nemeth, D. (2019). Structure detection in pseudorandom sequences: Implicit memory transfer of transitional statistics. *International Conference on Interdisciplinary Advances in Statistical Learning*, San Sebastian.
5. **Kóbor, A.**, Horváth, K., Kardos, Z., Takács, Á., Janacsek, K., & Nemeth, D. (2018). Sensitivity to probabilistic regularities during procedural learning: ERP evidence. *4th Conference of the European Society for Cognitive and Affective Neuroscience*, Leiden.
6. Horváth, K., Kardos, Z., Takács, Á., Janacsek, K., Nemeth, D., & **Kóbor, A.** (2018). Error monitoring in explicit probabilistic sequence learning. Communication, Pragmatics, and Theory of Mind: *X. Dubrovnik Conference on Cognitive Science*, Dubrovnik.