Budapest University of Technology and Economics

PhD School in Psychology

Cognitive Psychology

Input effects and methods of measurement in statistical learning

Thesis booklet

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Budapest, Hungary, 2023

Studies included in the thesis

Study 1:

Lukics, K. S., & Lukács, Á. (2022). Modality, presentation, domain and training effects in statistical learning. *Scientific Reports, 12*(1), 20878.

Study 2:

Lukics, K. S., & Lukács, Á. (2021). Tracking statistical learning online: Word segmentation in a target detection task. *Acta Psychologica, 215,* 103271.

Study 3:

Lukács, Á., Dobó, D., Szőllősi, Á., Németh, K., & Lukics, K. S. (2023). Reading fluency and statistical learning across modalities and domains: online and offline measures. *PLOS One, 18*(3), e0281788.

Introduction and main objectives of the studies

Statistical learning is the ability to extract patterns and regularities from the environment through observation based on frequency distributions and transition probabilities in an unsupervised manner (Aslin, 2017; Frost et al., 2015). Although this ability is assumed to be crucial in shaping human cognition and everyday behavior (e.g., Conway et al., 2010; Daltrozzo et al., 2017; Kidd, 2012; Kidd & Arciuli, 2016; Misyak & Christiansen, 2012; Ren et al., 2023; Sherman et al., 2020), the exact nature and methods of assessing statistical learning have been the subject of ongoing debate.

Given its widespread occurrence across different areas of cognition (Conway et al., 2010; Conway & Christiansen, 2005; Hunt & Aslin, 2001; Reber, 1967; Saffran, Aslin, & Newport, 1996; Tillman & McAdams, 2004), it is reasonable to assume that statistical learning is a domain-general construct that operates across different cognitive domains and modalities. Nonetheless, accumulating evidence suggests that statistical learning may be influenced by the specific domain, modality, and stimulus in which it occurs (Conway & Christiansen, 2006; 2009; Hendricks et al., 2013; Walk & Conway, 2016), suggesting domain-, modality-, and stimulus-specific constraints and autonomous operation in different areas. However, there is a lack of comprehensive studies investigating the different aspects of domain specificity versus generality, making systematic research on this matter necessary.

Despite the hypothesized importance of statistical learning in human cognitive functioning, well-established assessment methods of learning capacity are also lacking, making it challenging to test its contribution to different skills and behaviors. The most commonly used judgment-based measurement methods have shown issues with reliability and validity (Batterink et al., 2015; Batterink & Paller, 2017; Franco et al., 2015; Isbilen et al., 2017, Siegelman et al., 2017; Siegelman & Frost, 2015). Although considerable efforts have been made to find better assessment methods (e.g., Batterink, 2017; Bertels et al., 2012;

Franco et al., 2015; Isbilen et al., 2017; Lammertink et al., 2019; Siegelman et al., 2018), there is still no consensus on a generally accepted measure of statistical learning.

Questions about the nature and measurement of statistical learning are closely intertwined: accurate measurement methods are essential for gaining insight into the operation of statistical learning, and conversely, understanding what statistical learning is is indispensable for developing appropriate measurement approaches. Accordingly, our goal throughout three studies was to contribute to a better understanding of the nature of statistical learning, with two main foci: 1) understanding modality- and domain-specific constraints on statistical learning, and 2) exploring methods for effectively measuring this form of learning.

In **Study 1**, we conducted a systematic investigation of the effects of modality and domain on statistical learning in an artificial grammar learning task. Previous research has indicated that the modality and domain of the input influence statistical learning, but systematic investigations of domain effects on statistical learning are scarce. Conducting systematic investigations is crucial as it allows us to test multiple research questions about modality and domain generality versus specificity under controlled conditions, in contrast to distinct studies that employ diverging methods. In our study, we systematically manipulated modality (auditory versus visual) and domain (linguistic versus non-linguistic), and further explored how different exposure manipulations influenced statistical learning of stimuli from various modalities and domains. These manipulations included variations in presentation type (serial versus simultaneous presentations of sequences in the visual modality) and training type (the order of presentation of sequences with different lengths: random, starting small and starting big).

In **Study 2**, we implemented the target detection method to examine statistical learning in an auditory word segmentation task. The commonly used judgment-based tasks (also applied in Study 1) are associated with several methodological limitations, including concerns

related to their reliability and validity, which may compromise the interpretability of findings. To address these limitations and identify a more suitable approach for studying statistical learning, we applied the target detection method to a word segmentation task. This method holds promise in mitigating some of the confounding factors associated with other testing approaches, as it is less susceptible to cognitive factors unrelated to statistical learning, allows for tracking of the learning process, and addresses concerns associated with post-hoc testing, such as extended learning and unlearning effects during the test phase. We examined the applicability of this method, investigated its relationship with the judgment task and a short-term recall task, and also assessed the reliability of all these measures.

In **Study 3**, our objective was to investigate the association between statistical learning and reading ability using our target detection paradigm both in the auditory linguistic and the visual nonlinguistic domains. Statistical learning is hypothesized to underlie language skills. Findings demonstrating a relationship between these two constructs support this hypothesis. However, most studies exploring the relationship between statistical learning and language have relied on judgment-based tasks to assess statistical pattern acquisition performance. These tasks have limitations due to their weak psychometric properties, rendering them unsuitable for evaluating individual differences. Moreover, judgment-based tasks pose particular challenges when assessing individuals with developmental and linguistic difficulties, as in their case, other cognitive capacities may also be impaired, potentially confounding task performance (Archibald & Gathercole, 2006; Marton & Schwartz, 2003; Montgomery, 2003; Smith-Spark & Fisk, 2007). Hence, there is a need to employ tasks with stronger psychometric properties. In our study, we utilized both the online target detection task and a judgment-based task to assess auditory linguistic and visual nonlinguistic statistical learning capacities in Hungarian adolescents with varying levels of reading ability. We

assumed that as both auditory and visual statistical learning abilities are important in shaping reading skills, they independently contribute to differences in reading fluency.

Thesis points

Thesis I. Statistical learning has modality and domain-specific constraints (Study 1).

In Study 1, we found domain effects in the statistical learning of an artificial grammar. Specifically, we found that learning was more efficient in the auditory modality compared to the visual modality when stimuli were presented serially. Furthermore, this modality effect was more prominent with linguistic stimuli compared to non-linguistic stimuli. However, when visual sequences were presented simultaneously, there was no advantage of auditory stimuli for learning. Moreover, statistical learning of the artificial grammar with linguistic stimuli led to superior performance compared to non-linguistic stimuli, but this language effect was only evident in the auditory modality. Overall, the auditory linguistic condition exhibited an advantage over other conditions. In addition to general modality effects on statistical learning, we identified a specific training effect of stimulus modality. In the visual modality, initiating training with longer stimulus sequences (*starting big* training) resulted in improved performance in the case of serial presentation compared to commencing with shorter stimulus sequences (*starting small* training). Also, *starting small* training resulted in lower performance in serially presented sequences compared to simultaneously presented sequences. In contrast to the visual modality, no training effect was observed in the auditory modality.

Thesis II. Beyond modality and domain, stimulus type also influences statistical learning (Study 1).

There are different types of stimuli in the environment based on their physical and structural characteristics, but also based on which of their features are relevant from the learner's perspective (e.g., spoken language, music, human faces, etc.). While some stimulus types may belong to the same modality and domain (e.g., music and environmental sounds),

they may still be subject to different learning constraints. In Study 1, we observed results that were more likely due to stimulus type effects than to effects of modality and domain.

We found that statistical learning of the artificial grammar using auditory non-linguistic stimuli resulted in lower performance compared to learning with either auditory linguistic or simultaneous visual non-linguistic stimuli. Notably, in the auditory non-linguistic condition, we employed musical tones as stimuli, which introduced emergent musical features such as contours (i.e., ascending and descending patterns between tones) and intervals (i.e., relative pitch changes between tones). These musical features may have either supported or conflicted with the statistical structure derived from the artificial grammar. Subsequent analyses indicated that the lower performance in the auditory non-linguistic condition may have been attributable to conflicting grammatical and musical patterns. Thus, our findings do not support the presence of general modality or domain effects in statistical learning, but instead suggest that the scope of these effects may be more constrained by the specific type of stimuli employed.

Thesis III. Online measures yield efficient and sensitive measures of statistical learning (Study 2, Study 3).

In Studies 2 and 3, in response to concerns regarding commonly used measurement methods, we employed the online target detection task as a novel measurement approach within the segmentation paradigm. In both studies, the target detection task revealed significant online learning effects, as evidenced by changes in reaction times. Specifically, reaction times decreased during the training phase, increased during an unstructured block, and then decreased again during a structured recovery block. The online tracking of learning further demonstrated that the acquisition of statistical patterns is gradual, with reaction times progressively decreasing across the training blocks. The inclusion of a random block in the experimental design also allowed for control of general practice effects, as the presence of

statistical structures was the only distinguishing factor between structured and unstructured blocks, thereby attributing any reaction time differences between these blocks to the acquisition of statistical patterns.

In the context of our studies, measures such as *RT training* and *RT difference* scores serve as good indicators of individuals' performance improvements during training and in comparison to an unstructured reference block. In Study 2, we observed that online scores showed a comparable learning effect to two-alternative forced choice and short-term recall tasks in adult participants. In Study 3, with adolescent participants, we found evidence of learning effects in both online and offline tasks in the linguistic auditory condition. However, in the nonlinguistic visual task, online scores demonstrated learning despite modest learning effects in the offline task. In conclusion, our findings suggest that online target detection provides efficient and sensitive test scores in our experimental paradigm.

Thesis IV. Online measures of statistical learning are reliable (Study 2).

In Study 2, online measures, *RT training* and *RT difference* exhibited split-half reliabilities of r = .71 and r = .70, respectively. These levels of internal consistency were higher compared to the offline measures from the two-alternative forced choice task, which had a reliability of r = .58, and short-term recall measures, which had a reliability of r = .43. (These results were replicated in the second experiment of this study, which focused on the explicitness versus implicitness of the acquired knowledge.) Moreover, RT training and RT difference demonstrated sensitivity levels that were comparable to or even higher than 2AFC scores, suggesting that these measures are capable of detecting both smaller and larger learning effects. These findings suggest that the online measures exhibit favorable indices of internal consistency, making them a promising tool for future research, as it allows one to conduct more powered studies. This is particularly important in studies aiming at measuring

individual differences or comparing performance in different populations (e.g. clinical and typical, child and adult).

Thesis V. The target detection task is suitable for measuring statistical learning in the auditory linguistic as well as in the visual nonlinguistic domains (Study 3).

In addition to observing significant learning effects in the speech segmentation tasks in Study 2 and Study 3, we also identified a significant learning effect in the visual non-linguistic online task in Study 3. However, this learning effect was comparatively weaker than that observed in the auditory linguistic condition. These findings suggest that the target detection paradigm holds promise as a tool for measuring statistical learning in both the auditory linguistic and visual nonlinguistic domains, at least in adolescent populations.

Discussion

There has been a growing interest in statistical learning due to its presumed predictive power for everyday skills and behaviors (Conway et al., 2010; Daltrozzo et al., 2017; Kidd, 2012; Kidd & Arciuli, 2016; Misyak & Christiansen, 2012; Ren et al., 2023; Sherman et al., 2020). To gain deeper insight into how this form of learning contributes to the development of various skills and behaviors, or to profile special populations based on their statistical learning abilities, it is crucial to define the concept of statistical learning and to identify appropriate methods to assess it. In this thesis, we present three studies that aim to contribute to the understanding of statistical learning by investigating its nature and searching for better ways to measure it.

First, we found that statistical learning is influenced by modality and domain, as well as by the specific stimulus type. In particular, auditory and linguistic stimuli led to superior performance in the learning of an artificial grammar. Moreover, we observed that stimulus type may influence statistical learning beyond modality and domain, as suggested by the lower performance associated with conflicting structural information observed for auditory nonlinguistic stimuli. The results suggest that the constraints on statistical learning are influenced by the type of stimulus in which the learning occurs, supporting the notion that the optimal acquisition of a given structure depends on the stimulus type. Our results are consistent with the idea that statistical learning is best understood as a part of information processing in different domains and stimulus types rather than one learning mechanism that manipulates stimuli differently across stimulus types (Chang & Knowlton, 2004; Conway & Christiansen, 2006; Conway, 2020; Fiser & Lengyel, 2022; Hendricks et al., 2013). Conceptualizing statistical learning as an integral part of information processing can inspire new questions and hypotheses about the role of statistical learning in the buildup of specific skills and behaviors.

The second focus of the thesis was to improve the assessment of statistical learning. To this end, we used a target detection task as a novel approach within the segmentation paradigm. The target detection task was found to effectively capture online learning as evidenced by changes in reaction time and accuracy in both the auditory linguistic and visual nonlinguistic domains. Online indices derived from this task successfully demonstrated learning effects even when offline tasks showed modest performance. Furthermore, online indices in the auditory linguistic domain were found to reliably measure statistical learning. The dissociation between the online target detection and judgment-based 2AFC measures regarding their predictive role in reading abilities is consistent with the conceptualization of statistical learning as a multifaceted construct involving multiple mechanisms (e.g., Conway, 2020; Farkas et al., 2021; Siegelman et al., 2019). Taken together, our results underscore the necessity to understand the exact mechanisms underlying statistical learning in order to develop appropriate assessment methods.

In conclusion, our results expand our understanding of statistical learning, but together with previous findings, they also invite further questions and avenues of research. They highlight the importance of a psychometric perspective, which provides novel aspects and methods for examining this form of learning and helps us tease apart its components and gain good measures of individual differences. As a result, it may also help inform the selection of relevant hypotheses, stimuli, and designs for research on the relationship between statistical learning and other abilities.

Ultimately, improving our understanding of statistical learning and identifying appropriate measures is important both theoretically, for understanding the human cognitive structure and its individual differences, and practically, for developing interventions that target impaired everyday skills and behaviors that rely on this form of learning.

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