（様式 10）
（海外特別研究員事業）
平成 31 年 4 月 2 日

海外特別研究員最終報告書

独立行政法人 日本学術振興会 理事長 殿

採用年度 平成 29
受付番号 412
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（氏名は必ず自署すること）

海外特別研究員としての派遣期間を終了しましたので，下記のとおり報告いたします。
なお，下記及び別紙記載の内容については相違ありません。

記

1. 用務地（派遣先国名）用務地：マックス・プランク認知神経科学研究所 （国名：ドイツ国）
2. 研究課題名（和文）※研究課題名は申請時のものと違わないように記載すること。
   読唇と音声認知による言語統計学習の神経学的評価：失読症の言語機能の解明
3. 派遣期間：平成 29 年 4 月 1 日 ～ 平成 31 年 3 月 31 日
4. 受入機関
   受入機関: マックス・プランク認知神経科学研究所

8. 所期の目的の遂行状況及び成果　**書式任意（A4 判相当 3 ページ以上、英語で記入のものも可）**

（研究・調査実施状況及びその成果の発表・関係学会への参加状況等）

[1] 脳波を用いた失読症の早期診断法の開発

・Back ground

The human brain possesses an innate implicit learning mechanism, called statistical learning (SL). Using this mechanism, the brain automatically extracts regularities underlying the arrangement of elements within sequences (i.e., transitional probabilities between those elements). SL doesn't require any intention to learn and typically happens without awareness of what has been learned. Previous evidence indicated that children with Developmental Language Disorder (DLD) have deficiencies with using SL mechanisms.

・Objective

How auditory SL is reflected in Event-related potentials (ERP) in adults with and without Developmental Language Disorder.

- **Participants**: 9 adults with Developmental dyslexia and 20 control adults.
- **Stimuli**

2.3.1. Tone

Six pairs of sounds that consisted of shepard pitch tones (F3, G3, A3, B3, C#4 and D#4) and percussive tones (surdo, tambourine, agogo bells, hi-hat, castanet and woodblock) were prepared for exposition phase and behavioural tests. The combination of the pairs was counterbalanced across participants. Another set of six pairs of sounds (shepard pitch tones: E3, F#3, G#3, A#3, C4 and D4; percussive tones: woodblock, tambourine, agogo bells, castanet, hi-hat and bass drum) was used for practice phase at the beginning of the experiment. An additional target sound (C#5) was used for a cover task in which participants were asked to execute during both the practice and exposition phases. The other parameters were constant (duration = 220 ms, rise/fall = 10/20 ms, same loudness).

Table 1

		Transitional probability	
		High	**Low**
Sound Location	**Standard**	Standards	Statistical Deviant
	Deviant	Physical Deviant	Double Deviant

2.3.2. Sequence

The pairs of sounds (hereinafter, referred to as A to F) were combined into sound triplets. In Figure 1, the A, B, C and D were used for the first two items of each triplet (AB and CD, referred to as root), while the E and F were used for the last item of each triplet (ending, referred to as ending). In the end, four types of triplets were prepared. The combination of triplet items (roots and endings) was counterbalanced across participants as a way to guarantee that any acoustical differences between sounds will not bias the grand-average brain responses. The sequence was 400 repetitions of the triplets (stimulus onset asynchrony = 300 ms, duration = around 7 min) with two constraints of occurrence. First, the triplets were sequenced based on probability ratios of 90 and 10% (Figure 1). Thus, the transitional-probability (TP) ratio of the endings (E and F) is 90 and 10%. Second, the 90% of the six items (A to F) were presented from either left or right side of speakers that forms an azimuthal angle of 60° between the speakers, whereas the 10% of them were presented from the other side. In the end, 2 x 2 categories of triplet ending occurred (Table 1). In addition, a triplet with low TP of ending was followed by at least three triplets with high TP, and a same triplet was not adjacently repeated.

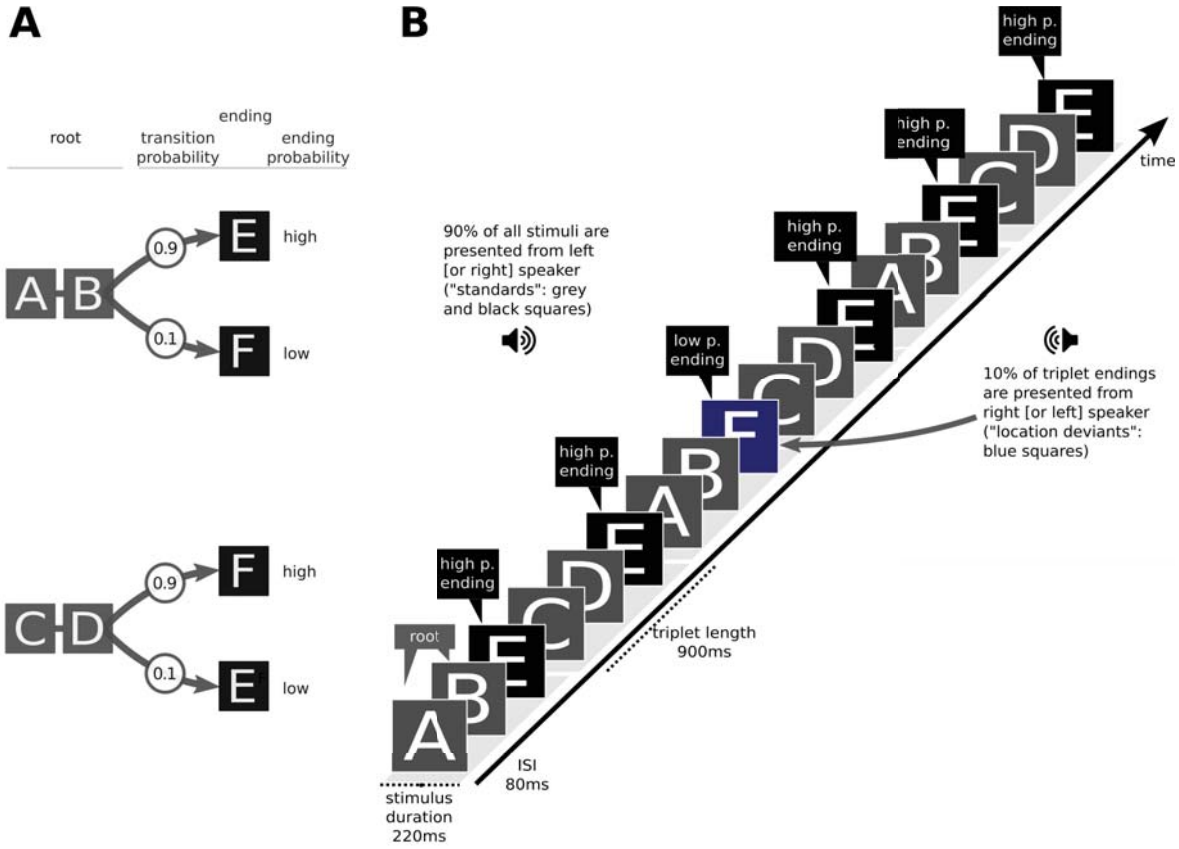


Figure 1. A. The triplets in the present study. The first two items of the triplet are named root and the last item is name ending. The transition probabilities of ending are high 90 or 10% based on the root. B. The example of sequence with statistical deviants of ending (letter in blue box) based on TP and physical deviants based on sound location.

- **Procedure**

The experiment consisted of 6 blocks that consisted of an exposition phase followed by a behavioural test. The participants were shown a silent movie on the monitor in front of them during the exposition phase in which auditory stimuli were presented from speakers. They were instructed to keep the eyes within the window of the movie. The experiment started with an instructions set followed by a practice phase of 1 minute. The practice phase was repeated in case participants did not score above 80%. As a cover task, participants were asked to press the key as soon as possible when they heard the target sound with high pitch.

In each of the 12 trials of the behavioural test, participants were presented two triplets with high and low TP of ending, respectively. There was a pause of 335ms between the two triplets in each trial. Note that the two triplets in each trial differed solely in the ending and there was no location change of the sound (i.e., [ABE and ABF] or [ABF and ABE] or [CDF and CDE] or [CDE and CDF]). They were then asked to choose which triplet sounded more familiar. Then, they were asked to rate confidential level of each answer, ranging from 1 (random) to 5 (certain). All four possible comparisons between the two triplet roots and the corresponding two triplet endings were presented three times (i.e., 4 x 3 = 12 trials).

Comparisons involving the same root were not repeated in consecutive trials and the order of presentation of the endings was counterbalanced. Responses were classified as correct when participants chose the sequence that was played more often during exposition phase, meaning the one with high probability ending. Mean percentage of correct answer in each participant was compared against chance level.

- **EEG data analysis**

The electroencephalogram (EEG) with 64 channels, cap-mounted in compliance with the extended 10-10 system was recorded inside a shielded chamber during whole experiment. Selective response averaging was conducted separately for low and high TP triplet endings with or without location change of the sound. The electrodes were clustered into nine regions of interest (ROIs), namely frontal left (F7, F5, F3, FT7, FC5, FC3), frontal middle (F1, FZ, F2, FC1, FCZ, FC2), frontal right (F8, F6, F4, FT8,

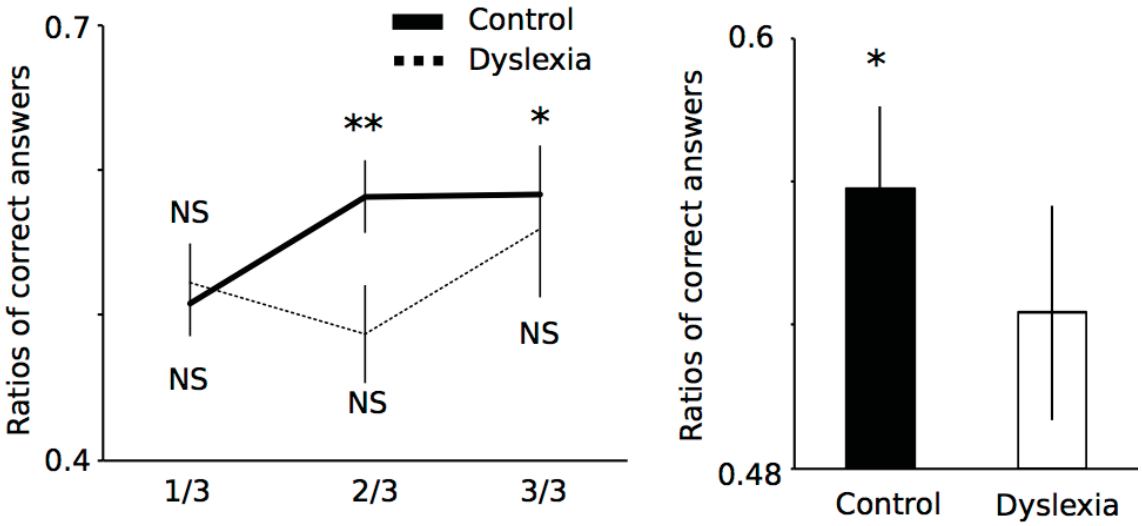
FC6, FC4), central left (T7, C5, C3, TP7, CP5, CP3), central middle (C1, Cz, C2, CPZ), central right (T8, C6, C4, TP8, CP6, CP4), parietal left (P7, P5, P3, PO7, PO3, O1), parietal middle (P1, PZ, P2, POZ, OZ) and parietal right (P8, P6, P4, PO8, PO4, O2).

Four analysis of variance (ANOVA) were conducted respectively, for transition probability deviants, physical deviants, the interaction between these two and the segmentation. The main within-subjects factors varied accordingly and three factors were standard in all analysis. These were cortex area (frontal, central, posterior), lateralisation (left, medial, right) and experiment block (3 blocks instead of the actual 6 blocks of the experiment in order to obtain higher signal to noise ratio).

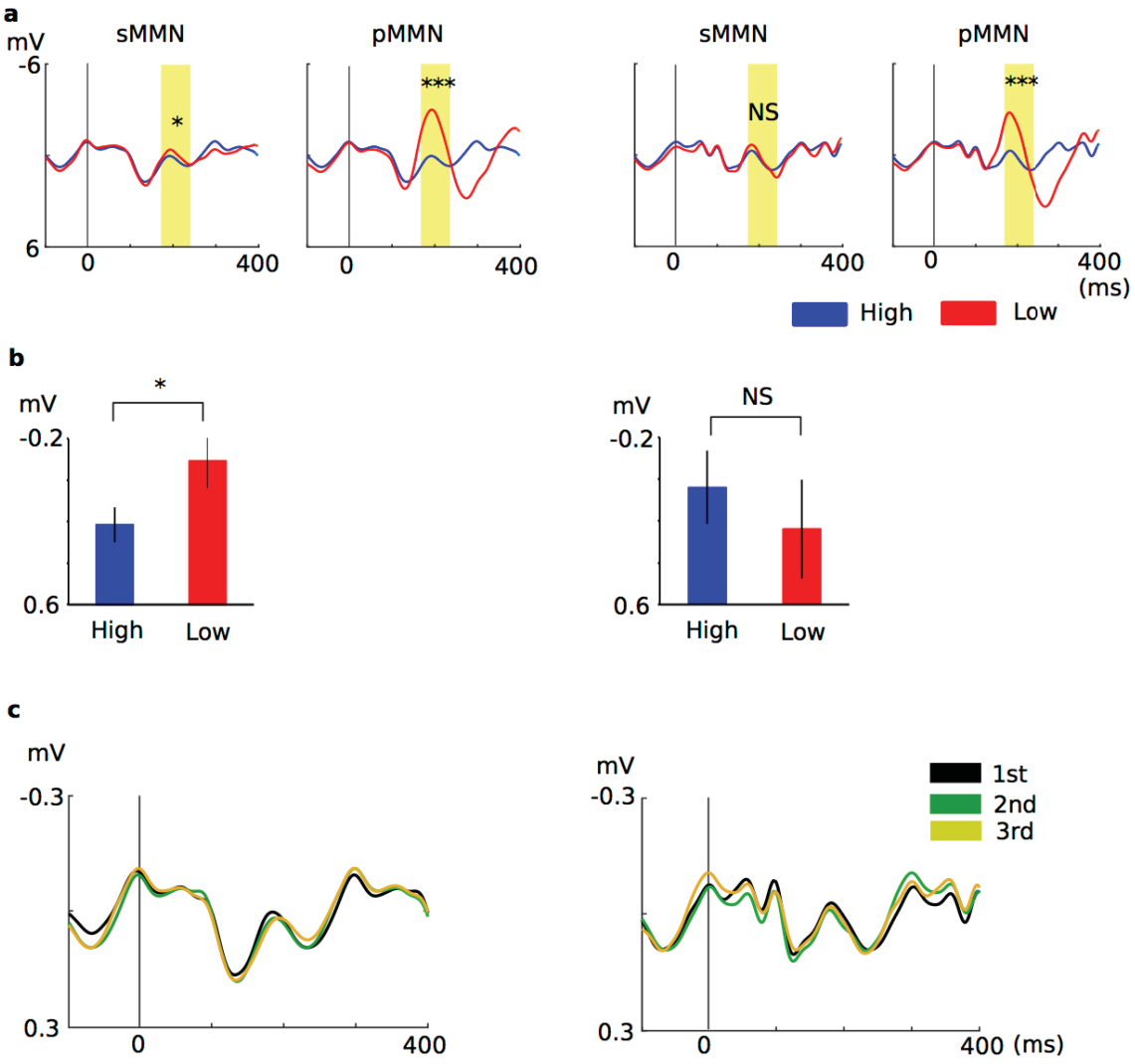
・Result

In both behavioural and neuronal responses, statistical learning effects in dyslexia was less than those in control.

Behavioural result



Neuronal result



Duscussion

- One ERP component, the statistical mismatch negativity (sMMN), reflected differences in brain-electric activity to stimuli with higher vs. lower transitional probability.
- It had negative polarity peaking at approximately 150–250 ms after the onset of the stimulus.
- Our studies aimed to establish experimental paradigms to explore SL in children and to determine whether these could be indicative of differences between typical and delayed language development.
- This could open a perspective for better insight in mechanisms underlying the disorder and for applications in early detection and intervention for children suffering from DLD.

[2] 脳波を用いた読唇メカニズムの解明

・研究・調査実施状況

図 1.実験に使用するパラダイム

データは全て取得し、解析もほぼ終わった(図 2)。Meeting にて、結果自体があまり面白みにかけるため、別の解析法も用いてみようという話になり、現在解析の勉強中である。

また、共同研究者の受理済みの論文の再解析を行い、興味深い結果が出たので論文にし、現在査読中である。

・成果の発表

オランダで開かれた speech motor control 学会にて学会発表を行った。

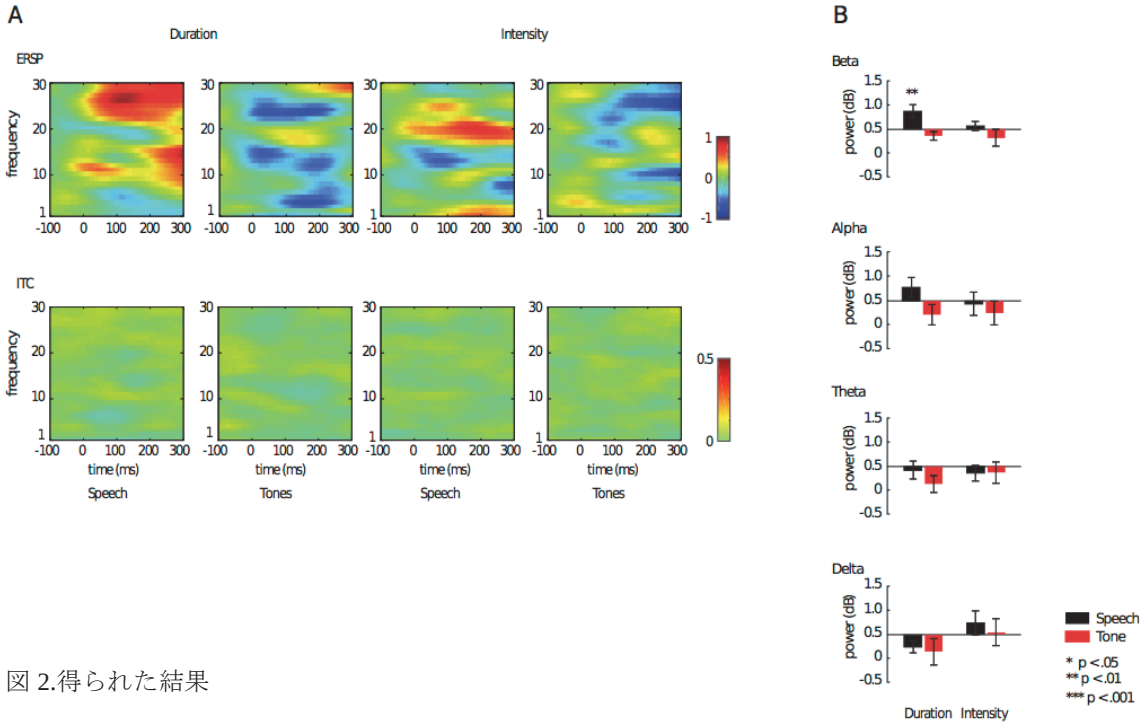


図 2.得られた結果

[3] 統計学習の心的表象の計算論的解明

・研究・調査実施状況

最近のデータによると、特に言葉の読み書きに困難を示す失読症は、世界の人口の 3-7%に発症していると報告されている。ヒトの言語処理メカニズムの解明と失語症の発症機序の解明、そしてそれらを対象とした効率的な言語学習リハビリテーションの検討が迫られる。その解決策の一つとして、ヒトに生得的な自動言語学習システムであり、失読症で機能が低下する**統計学習**が考えられる。本研究にて、失読症の統計学習機能低下が言語処理機能低下を引き起こすメカニズムとの関係性を明らかにするためには、ヒトの統計学習の心的表象を計算論的に研究することも必要であると考えた。そのため、まず申請者は、python を用いて、文章や音楽の楽譜から統計的情報を抽出するシステムを考案した(日本、アメリカで特許申請中)。そしてそのシステムを用いて、数千の言語・音楽情報を解析し、統計知識の心的表象モデルを考案した(図 3)。現時点では、思考の深さと、統計学習のの階層の深さが関係あるのではないかと推測している。得られた結果は、7 つの論文にし、現在査読中である。

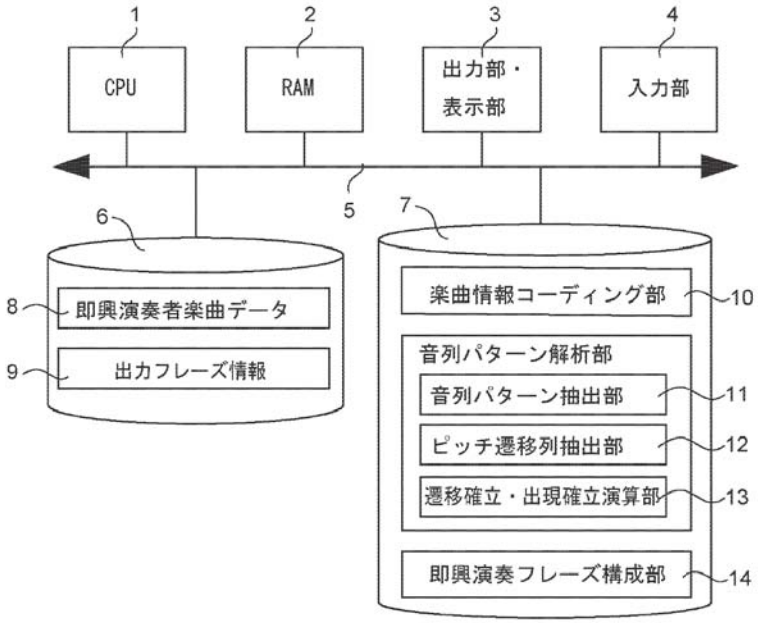


図 3. 特許の内容

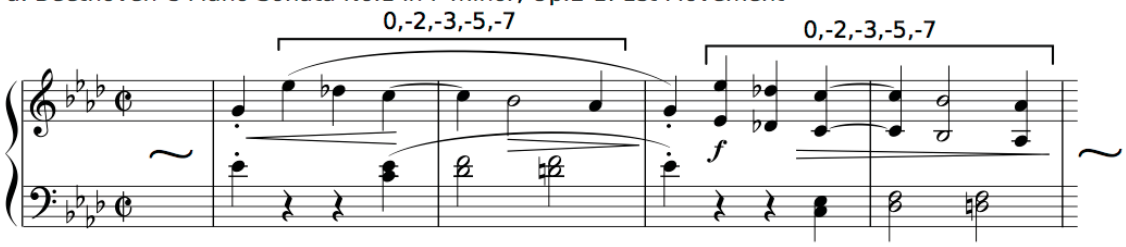
・成果の発表

6 月に、統計学習に関する計算論研究者の研究室(スイスのチューリッヒ工科大学、イギリスのロンドン大学)にてプレゼンテーションを行う予定である。発表が英語であることと、この研究分野は国内ではほぼ皆無のため、正確な表現のために全ての結果・発表内容を以下、英語にて簡潔に説明する。

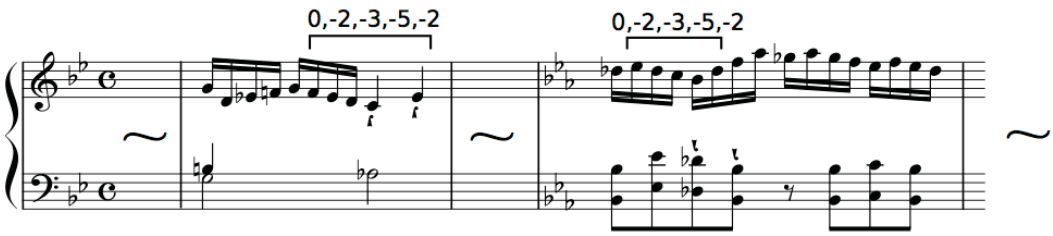
Result. 1

Learning and knowledge of transitional probability in sequences like music, called statistical learning and knowledge, are considered implicit processes that occur without intention to learn and awareness of what one knows. This implicit statistical knowledge can be alternatively expressed via abstract medium such as musical melody, which suggests this knowledge is reflected in melodies written by a composer. This study investigates how statistics in music vary over a composer's lifetime. Transitional probabilities of highest-pitch sequences in Ludwig van Beethoven's Piano Sonata were calculated based on different hierarchical Markov models. Each transition pattern was ordered based on the musical number. The transitional probabilities of sequential patterns that are familiar in music gradually decreased, suggesting that time-course variations of statistics in music reflect time-course variations of a composer's statistical knowledge. This study sheds new light on novel methodologies that can be employed to evaluate implicit knowledge of a composer using musical scores.

a. Beethoven´s Piano Sonata No.1 in F minor, Op.2-1: 1st Movement



b. Beethoven´s Piano Sonata No.32 in C minor, Op.111: 1st Movement



Result. 2

The learning and knowledge of transitional probability in sequential information such as music—called statistical learning and knowledge—can be considered an implicit system regardless of consciousness. Jazz musicians can intuitively engage in musical improvisation based on their knowledge and experience. This improvisation does not necessarily follow explicit knowledge of music-specific rules, which suggests that implicit knowledge may underlie their improvisation. This study investigated how implicit knowledge is reflected in musical improvisation. The results suggest that the time-course variations of statistical structures in music may represent the time-course variations of a musician's implicit knowledge by which a forthcoming tone is statistically defined. Second, there may be specific statistical characteristics that are shared between distinct pieces of music in the same title played by different musicians and between pieces of music in distinct titles played by the same musician. Third, the musical improvisation of a musician may influence the higher-order hierarchical implicit knowledge of other musicians without explicit intention and awareness. The present study sheds new light on novel methodologies that can be employed to evaluate how implicit knowledge and creativity in a musician are influenced by other musicians using musical scores in interdisciplinary studies that include psychology, informatics, and musicology.

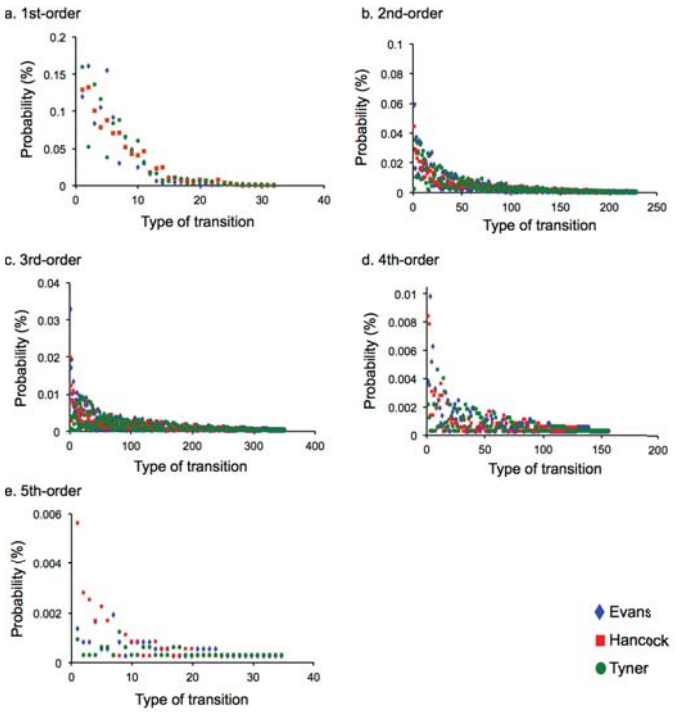


Figure. The transition [illegible] vans, H. J. Hancock, and M. Tyner. The horizontal and vertical axes represent the types of transitions and the transitional probabilities, respectively. The transition patterns were arranged in the descending order of transitional probabilities.

Result. 3

Implicit knowledge, which is unconsciously inherent in humans, is considered the knowledge of transitional probability (TP) in sequential information such as music. Although this knowledge does not reach the level of an explicit awareness of what we know, it is alternatively expressed via abstract media such as musical melodies, suggesting that this knowledge is reflected in melodies written by a composer. This study examined how implicit knowledge is reflected in music, and how it interacts with musical tonality. The statistical structure of TPs in the pitch sequences of Johann Sebastian Bach´s Well-Tempered Clavier were calculated based on six different TP hierarchical models. In the lower hierarchical levels of the statistical structure, all the pieces of music were related to each other. However, the higher the hierarchical levels of the TPs, the less the music was correlated with each other. These findings suggest that the general statistical structures that are shared among many pieces of music is formed by low-hierarchical implicit knowledge, whereas the specific structures that are independent in each piece of music are formed by high-hierarchical implicit knowledge. The principal component analysis detected the components of related keys, suggesting that tonalities modulate implicit knowledge. Implicit statistical and explicit music-specific knowledge could interact with each other. This study has shed new light on novel methodologies that can be employed to evaluate the implicit knowledge of a composer using musical scores in interdisciplinary studies that include psychology, informatics, and musicology.

Result. 4

Statistical learning is a learning system of transitional probability, and is considered an universal process that is innate in humans. Acquired knowledge can be alternatively expressed via an abstract medium such as musical melody, which suggests that this knowledge is reflected in melodies written by a composer. In the framework of statistical learning, a higher-probability sequence in music may be one that a composer is more likely to choose. In this context, this study investigates how statistics in music vary among periods of a composer's lifetime. The results suggested the composer's psychological desire related to novel music affected the higher-, but not lower-, order statistical knowledge. Lower-order statistics may reflect elemental statistical knowledge that is not affected

by psychological variations whereas higher-order statistics may reflect statistical knowledge susceptible to psychological variations. This study shed new light on a novel approach to evaluate statistical knowledge of a composer via interdisciplinary approaches.

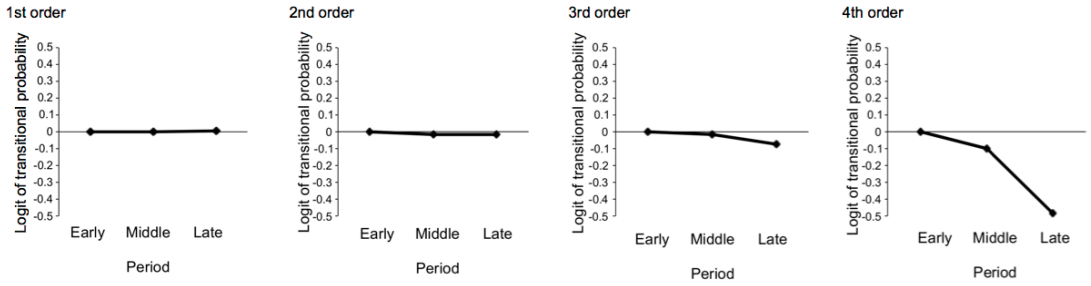


Figure. The variations of TPs in sequences that are shared among all of Beethoven's piano sonatas.

Result. 5

The general hypothesis of statistical learning is that the brain automatically calculates the transitional probabilities of sequences such as speech and music, and predicts a future state using the learned statistics. It has been suggested that the sequence of musical improvisation is in part formed by a composer's statistical knowledge, regardless of intention: a high-probability sequence may be one that a composer is more likely to choose compared to a low-probability sequence. The present study investigates the differences in the transitional probabilities of improvisational sequences among musicians, and discusses the relationships between musical improvisation and statistical knowledge. The findings showed the individuality of improvisation for each musician, which in part depends on the statistical knowledge that is associated with the procedural learning involved in statistical learning. The present study sheds new light on novel methodologies that can be employed to evaluate how the musical improvisations of a musician are influenced by others via statistical learning, using interdisciplinary approaches.

Result. 6

An increasing amount of evidence shows that musical representation is mainly formed by implicit knowledge. Particularly, improvisation forces a musician to play their own music based on intuitive decision-making and auditory-motor planning associated with implicit knowledge. However, types of spectro-temporal features and depth of knowledge forming individualities of improvisation are unknown. This study, using various-order Markov (ngram) models on implicit learning, investigated spectro-temporal statistics among musicians. First, lower-order implicit knowledge represented general characteristics shared among musicians, whereas higher-order implicit knowledge detected specific characteristics unique to each musician. Second, individuality of improvisation may essentially be formed by pitch but not rhythm implicit knowledge, whereas the rhythms may allow the individuality of pitches to strengthen. Third, time-course variation of implicit knowledge and general uncertainty expressed by entropy may occur in a musician's lifetime. Individuality of improvisational creativity may be formed by deeper but not superficial implicit knowledge of pitches, and that the rhythms may allow the individuality of pitches to strengthen. Individualities of musical implicit knowledge may shift over a musician's lifetime via experience and training. This study first provides hierarchical implicit-learning model that unifies temporal and spectral features in improvisational creativity, and that is interdisciplinarily verifiable using neurophysiological and computational approaches.

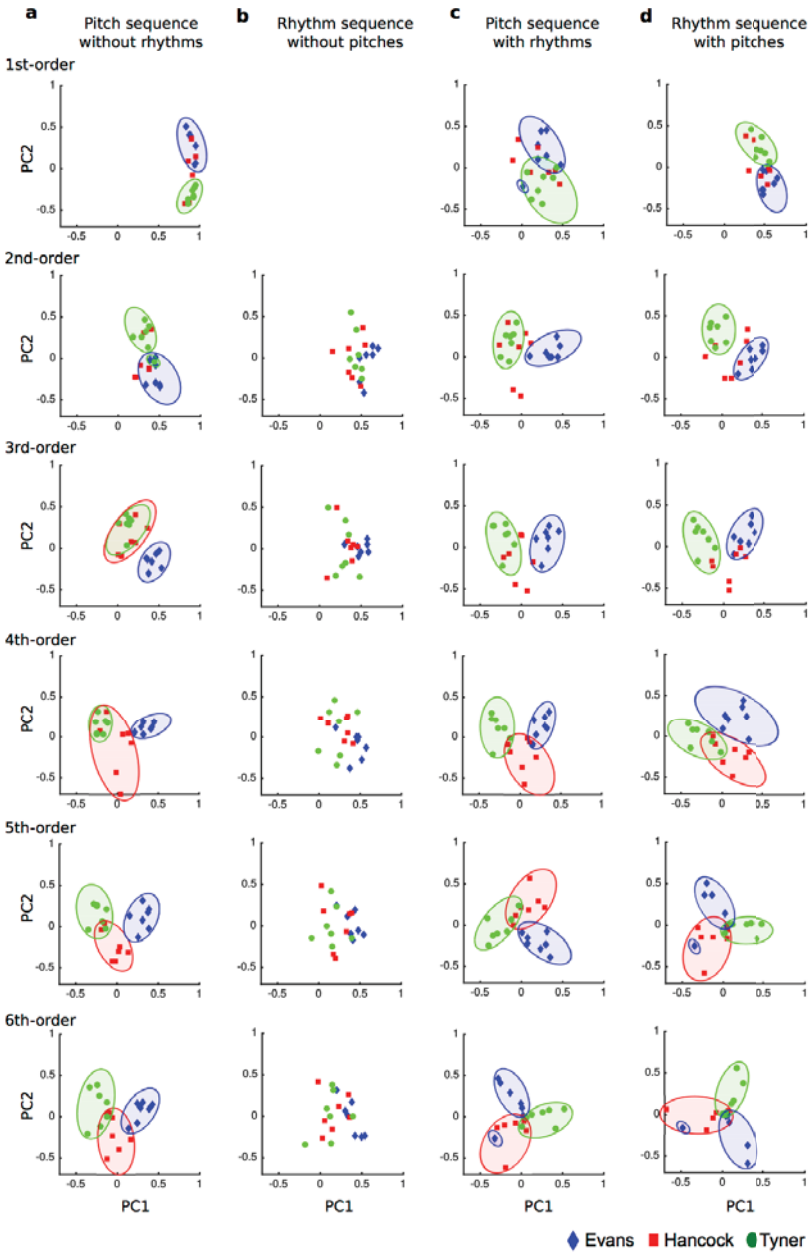


Figure. Principal component analysis scatter plots in pitch sequence without rhythms (a), rhythm sequences without pitches (b), pitch sequence with rhythms (c), and rhythm sequence with pitches (d). The horizontal and vertical axes represent principal component 1 and 2, respectively. The dots represent each piece of music.

[4] 統計学習の文化間での差異

・研究・調査実施状況

統計学習は、ヒトに普遍的な学習メカニズムである一方、生まれや育ちによっても能力に差が生じると報告されている。本研究テーマでは、失読症の解明ではあるが、今後国際的な客観評価法を開発するにあたり、文化間の違いを明らかにすることが大切であると考えた。邦楽家、西洋音楽家、非音楽家で統計学習の差異を調べた所、文化間では差が生じず、むしろ文化にかかわらず音楽教育歴の有無で統計学習機能に差異が生じることがわかった(図 6)。

・成果の発表

結果に関しては、biomagnetic にて学会発表を行った。

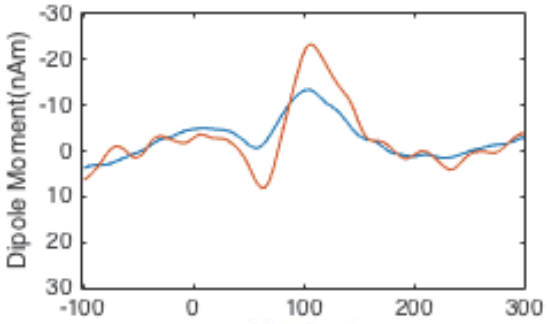


図 6. 音楽家の統計学習中の脳波

[5] 統計学習の心的表象の神経生理学的解明

・研究・調査実施状況

[3]では、計算論によって研究を行ったが、人間の機能を調べるためには実際の神経生理学的な検証も必要である。マックスプランク研究所の別ラボでは、ヒトの意思決定時の脳波活動計測を行っており、今後、本研究テーマである統計学習と意思決定に関する共同研究を行うことになった。現在、パラダイムを考案中である。問題点としては、計測中にオンラインで、心的表象の計算をするためのプログラミングが難しいことである。その点に関しては、プログラマーを呼び、現在解決法を探っている。