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学位論文題目 Selective enhancement of neural response consistency  
through self-organisation

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# 博士論文の要旨

氏 名：後藤 優仁

論文題目：Selective enhancement of neural response consistency through self-organisation

Perception is typically consistent: when the same sensory input is encountered again, subjective experience tends to be similar. Experimental neuroscience implicitly relies on a related assumption—that stimulus-evoked neural activity contains a consistent component that can be recovered from noisy recordings, for example, by averaging across trials. Yet such consistency is not guaranteed for a high-dimensional, recurrent, and intrinsically fluctuating system such as the brain. Neural activity varies across multiple scales, from local circuits to large-scale networks, and a growing literature argues that such variability is not merely a nuisance but can be functionally important, supporting flexible dynamics. The brain, therefore, faces a dual requirement: it must remain globally flexible while achieving strong input-conditioned consistency when needed. How this dual requirement is realised remains unclear.

In this thesis, I propose the selective consistency hypothesis: through experience, the brain selectively increases stimulus-conditioned neural consistency for a subset of inputs via synaptic self-organisation, and this selective increase supports more consistent perception for those inputs. This hypothesis is motivated by (i) evidence that response consistency is not fixed but can change with development and experience, and (ii) findings from perceptual learning paradigms in which perceptual selective consistency improves rapidly for complex stimuli that are difficult to explain through conventional feature-based accounts. The central behavioural model paradigm in this thesis is the noise-repetition detection (NRD) task, in which listeners judge whether concatenated white-noise segments are identical within a trial. A characteristic finding is that performance improves selectively for a repeatedly encountered exemplar, indicating experience-dependent gains in perceptual consistency for that specific stimulus.

To test the selective consistency hypothesis from complementary angles, I conducted (1) a computational simulation study and (2) a human electroencephalography (EEG) study during NRD performance.

In the simulation study, I examined whether a recurrent neural network can acquire selective consistency through local plasticity. Using an echo state network framework with weak Hebbian (Oja-type) plasticity in recurrent connectivity, I presented input time series analogous to NRD stimuli. The network developed higher selective consistency for repeatedly experienced inputs, while its responses to non-repeated inputs changed little. Importantly, this effect emerged without optimisation with respect to an explicit task objective, supporting the possibility that selective consistency can arise through self-organising dynamics. The magnitude of selective consistency acquisition depended on the network's baseline dynamical regime: it was maximised near criticality, at the boundary between overly ordered and overly chaotic dynamics (with the optimum

slightly biased towards the chaotic side, where  $\rho = 1.4$ ,  $p < 0.001$ ). In more ordered (e.g.,  $\rho \approx 0.9$ ) or more chaotic regimes (e.g.,  $\rho \approx 1.9$ ), selective consistency was not observed. This result motivates the idea that intrinsic network properties can constrain a system's capacity to acquire selective consistency.

In the EEG study, I tested whether neural and perceptual selective consistency develop together during NRD, and whether individual differences in learning relate to intrinsic neural properties. Following preregistered procedures, I collected behavioural and EEG data from 24 naïve participants (19 females, with an average age of  $34.17 \pm 9.02$  years, range = 21–45) while they performed the NRD task. Participants listened to sounds composed of concatenated white-noise segments and judged on each trial whether the segments were identical. Behavioural results showed a significant learning effect: repeated-measures ANOVAs revealed a main effect of stimulus type on hit rate ( $F_{1,23} = 5.42$ ,  $p = 0.029$ ,  $\eta^2 = 0.191$ ) and on  $d'$  ( $F_{1,23} = 12.19$ ,  $p = 0.002$ ,  $\eta^2 = 0.346$ ), with no Type  $\times$  Session interactions (hit rate:  $F_{2,46} = 1.02$ ,  $p = 0.367$ ;  $d'$ :  $F_{2,46} = 1.46$ ,  $p = 0.242$ ). Perceptual reports of repetition were associated with higher within-trial neural consistency in sensory and parietal regions in broadband activity (theta, alpha, beta, with the most robust effect of beta: FDR corrected  $q \ll 10^{-6}$ ). Conversely, perceptual reports of repetition were associated with lower within-trial consistency in delta-band activity in the parietal region (FDR corrected  $q \leq 0.035$ ). These relationships strengthened for the repeatedly encountered stimulus as learning progressed (temporal and parietal beta:  $q \ll 10^{-6}$ ; parietal delta:  $q \ll 10^{-9}$ ). In addition, delta-band phase analyses revealed stimulus-specific inter-trial consistency in correct trials for the learnt stimulus, but only in sessions in which learning was successful. Because phase-based measures index cross-trial consistency in the timing of neural activity, this pattern is consistent with the view that learning is accompanied by increased stimulus-specific consistency in task-relevant computations at the network level.

Across the two projects, the findings converge on two conclusions. Firstly, selective-consistency acquisition varies substantially across systems and individuals. In the EEG experiment, learning performance distribution significantly deviated from normality (Shapiro–Wilk:  $W = 0.85$ ,  $p = 0.0026$ ), with high interclass correlation across sessions, within-participant. Secondly, this variation is predictable from intrinsic properties of the underlying network: baseline dynamical regime in simulation and resting-state neural dynamics in humans. Given that disruptions of criticality have been linked to neurological and psychiatric conditions, the selective consistency framework suggests a principled way to reinterpret some impairments as constraints on the ability to acquire stimulus-specific consistency, rather than as simple increases in variability.

In summary, although the present work focused on a single paradigm (the NRD task), the results support the selective consistency hypothesis. Substantial challenges remain, including formalising the mathematical mechanisms by which selective consistency can be acquired through self-organisation, as well as linking the framework more rigorously to existing computational theories. Nevertheless, the hypothesis is attractive in that it proposes a mechanism for the brain's dual nature—overall flexibility/variability alongside stimulus-specific consistency—that emerges naturally as a dynamical property, without reliance on optimisation with respect to an explicit

objective function. Rather, considering conventional optimisation-based accounts of brain function exploit dynamical properties, selective consistency may serve as a foundational substrate for them. Moreover, because dynamical properties are constrained by underlying structure, this framework may help bridge structural-level findings relevant to disease with higher-level functional abnormalities. Thus, despite many open questions, the selective consistency hypothesis proposed here may pave the way for a new direction in neuroscience.

Results of the Doctoral Thesis Defense

## 博士論文審査結果

Name in Full

氏名 後藤 優仁

Title

論文題目 Selective enhancement of neural response consistency through self-organisation

出願者の後藤氏は、「同一の感覚刺激が入力された場合、刺激に誘発された同一の神経応答が生じ、同一の知覚が得られる」という神経科学における基本的前提に疑問を投げかけ、繰り返し提示される感覚刺激に対してのみ神経応答の一貫性 (consistency) が選択的に高まるという「選択的一貫性仮説 (selective consistency hypothesis)」を提唱した。

脳はその活動の初期状態やネットワーク構造の複雑性に強く依存する非線形力学系であり、初期値依存性を有するため、同一刺激に対して常に同一の応答を示すとは限らない。また、先行研究においては、同一刺激の反復提示により神経応答の一貫性や知覚的一貫性が獲得されることも報告されている。後藤氏は、この選択的一貫性仮説を、数理モデルを用いたシミュレーションによる研究 (研究 1) とヒト脳波実験による研究 (研究 2) の両面から検証した。

研究 1 では、リカレントニューラルネットワーク (Echo state network) に弱い可塑性 (ヘップ則) を導入したモデルを用い、繰り返し提示された刺激入力に対してのみ神経応答の一貫性が内発的に増強、獲得される計算論的メカニズムをシミュレーション研究で示した。さらに、この選択的一貫性の獲得は、ネットワーク結合行列から計算されるスペクトル半径が 1 近辺で臨界状態近傍にあるときに最大化されることが明らかとなった。

研究 2 では、ヒト実験参加者 (健康成人 24 名) を対象に、時系列内に反復構造を含むノイズ音刺激と、反復構造を含まないノイズ音刺激を用いた反復検出課題を行っている際の脳波を計測する実験を実施し、行動成績および脳波指標との関係を解析した。その結果、繰り返し提示される刺激条件において、学習の進行に伴い、試行間位相同期 (inter-trial phase coherence) で定量化される試行間の脳波一貫性と、単一試行内の反復ノイズセグメントに対応する脳波活動の一貫性が、いずれも選択的に増強され、知覚的一貫性の向上と対応することが示された。さらに、安静時脳波のパワースペクトルの傾きから推定したスペクトル指数を用いて、脳の臨界性の個人差が学習能力および一貫性獲得の個人差と相関する可能性も示唆された。

後藤氏はこれらの 2 つの研究により、反復刺激に対する神経応答および知覚の一貫性が一様に生じるのではなく、経験と脳の臨界性に依存して選択的に獲得されることを示した。このことは選択的一貫性の獲得が臨界状態近傍で最大化され、過度に安定あるいは不安定な力学状態では制限されることを示唆している。この選択的一貫性は、全体としての脳の変動性を保持しつつ、経験済み刺激に対する安定した表現と知覚的意思決定を可能にする力学的フィルタとして機能すると考えられる。

審査委員会は、脳が自己組織化的な可塑性を通じて、経験に基づき特定の刺激に対する神経応答および知覚の一貫性を選択的に獲得するという原理を提案し、さらに実験により計測されたデータとの整合性を検証した点において、本研究には十分な学術的価値および新規性が認められると判断した。以上の理由により審査委員会は全員一致で、本論文が学位の授与に値すると判断した。