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研究課題名（和文）A biological image generator: cuttlefish camouflage and visual perception

研究課題名（英文）A biological image generator: cuttlefish camouflage and visual perception

研究代表者
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研究者番号：６０８６９１５５

交付決定額（研究期間全体）：（直接経費） 4,700,000円

研究成果の概要（和文）：これまでの研究で、イカはわずかなカモフラージュパターンの中から目立つ背景画像の統計情報と最もよく一致するものを選んでいることが示されています。私たちは、イカのカモフラージュを定量的かつ客観的に説明するために、高解像度の撮影装置の構築および計算技術の設計を初めて行いました。その結果、イカのカモフラージュは、1）高次元である、2）高次の背景画像統計情報と正確に一致する、3）視覚フィードバックを利用していると考えられる蛇行探索を特徴とするダイナミクスを持つ、4）異なるカモフラージュ軌道で柔軟に再構成される色素体群からなる、5）単なる視覚脅威行動とは大きく異なることが分かりました。

研究成果の学術的意義や社会的意義
Our results push the boundaries of high-resolution filming of animal behavior, to study a system evolutionarily specialized to report the visual perception of animals which developed large brains independently of our own vertebrate lineage.

研究成果の概要（英文）：Previous work suggested that cuttlefish camouflage to their environments by choosing one of a small number of camouflage patterns that best match prominent background image statistics. We built a high-resolution filming array and designed computational techniques to describe cuttlefish camouflage quantitatively and objectively for the first time. Using these high resolution filming and computational techniques, we found that cuttlefish camouflage is instead 1) high dimensional, 2) able to precisely match higher order background image statistics, 3) has dynamics characterized by a meandering search, most likely utilizing visual feedback, 4) is composed of groups of chromatophores that are flexibly reconfigured during different camouflage trajectories, and 5) differs substantially from simple visual threat behaviors. These results will guide mechanistic studies of this remarkable texture-matching system.

研究分野：神経科学

キーワード：Visual perception Camouflage Cephalopod Eeep learning Psychophysics

１．研究開始当初の背景

Coleoid cephalopods (squid, octopus, and cuttlefish), possess the remarkable ability to change their skin pattern, texture, and body shape in order to blend in with the environment (camouflage). They do this primarily through employing large numbers of specialized skin cells called chromatophores, which can be expanded and contracted under control of their brains to produce different camouflage patterns[1]. They are not able to precisely match their environments 'pixel-wise', but instead are thought to extract a statistical summary of their surroundings (a visual texture), choosing a camouflage pattern out of a repertoire of patterns to match this background visual texture[2,3]. These animals thus provide a uniquely expressive readout of their visual perception, displayed as a 2-dimensional sheet on the animal's back. As this behavior is neurally controlled, understanding how cephalopods decide on a camouflage pattern, and how their motor system moves within camouflage pattern space presents a unique opportunity to record the complete output of a complex motor system performing a perceptual behavior. And since this behavior evolved to fool the visual systems of their vertebrate predators, and even works on disguising these animals from the human visual system, understanding cephalopod camouflage may reveal principles of our own visual perception.

２．研究の目的

The purpose of this project was to study the dynamics of camouflage behavior in cuttlefish. Previous research had been limited to static images of camouflaging animals at low resolution, and qualitative methods of describing camouflage patterns[4–6]. We developed novel methods for quantitatively describing the process of camouflage over time at the resolution of individual chromatophores and in terms of high-dimensional visual textures, overcoming these limitations. Using these techniques, we set out to provide a novel view of this remarkable system.

３．研究の方法

We developed quantitative behavioral techniques to describe cuttlefish camouflage dynamics at high-resolution. We built an array of 20 4k cameras shooting at ~10 microns/pixel, to film freely moving cuttlefish at a resolution high enough to resolve individual chromatophores. This array was placed on a two-dimensional rail system which could track an animal as it moved around a large experimental aquarium. We built a large roll of fabric which we could pass through the floor of the aquarium. On the fabric we printed a range of natural and artificial images as visual stimuli for the animal to camouflage.

After acquiring videos of cuttlefish camouflage with our camera array, we developed an analysis pipeline to extract the expansion state over time of tens of thousands of individual chromatophores in freely behaving cuttlefish (Fig. 1). This involved the use of nonlinear image stitching to fuse the images across the array into single large panoramas, neural networks for chromatophore segmentation, custom software for registering images over time. The result of this analysis was very large matrices of chromatophore data, which we analyzed to describe camouflage dynamics.

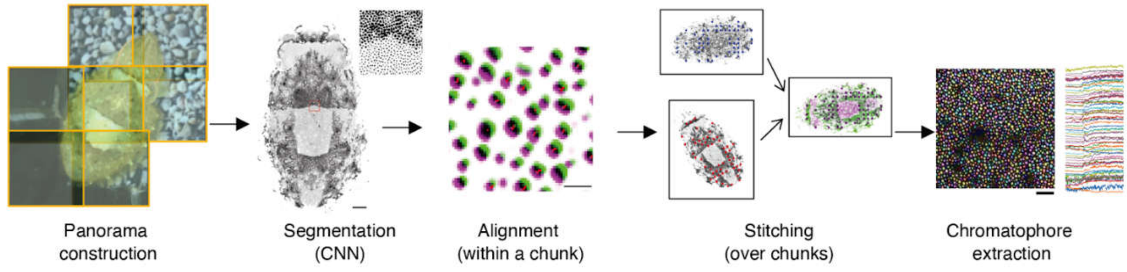
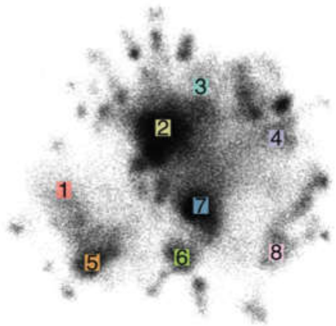


Fig. 1: Schematic of the chromatophore imaging pipeline.

The thin depth of field produced by our high-resolution filming meant that the animal would often move out of focus, making it impossible to measure camouflage dynamics. To overcome this issue, we placed a single overview camera on our array, synchronizing it with our high-resolution filming. The lower resolution video could not capture chromatophore scale dynamics but could capture much more of the dynamics of camouflage that we sought to describe. To quantify this data, we developed a novel high dimensional description of camouflage in terms of the representation of a neural network pre-trained on an object classification task[7]. Previous work had shown that this network learned an effective representation of visual texture[8], and we thus used this to describe the visual texture of cuttlefish camouflage, background images, and their match. Analysis of our behavioral data showed that this description of cuttlefish camouflage is more predictive of the animal's behavior than previous lower dimensional statistical descriptions.

４．研究成果

Previous work suggested that cuttlefish employ a small number of camouflage patterns, and a 'many to one' mapping from background visual textures to these patterns[3]. We collected hundreds of thousands of images of cuttlefish camouflaging to artificial and natural backgrounds, and quantified camouflage patterns using techniques described above. We were surprised to find that cuttlefish camouflage is high dimensional, with over 50 dimensions needed to explain the rich diversity of camouflage patterns. Nonlinear dimensionality reduction (UMAP) let us visualize camouflage pattern space, with similar points in this space corresponding to similar camouflage patterns (Fig. 2). Many patterns could be resolved quantitatively with our method in a way that eluded previous qualitative efforts.



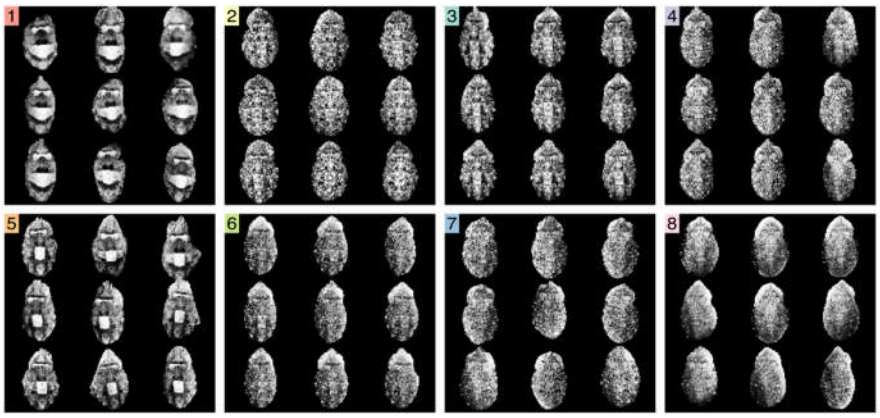


Fig. 2: Top, UMAP visualization of camouflage pattern space.
Bottom, Representative images taken from 8 regions of texture space.

We next investigated how camouflage pattern space relates to visual stimuli. Using a set of 30 natural images as well as a series of checkerboard patterns with different spatial frequencies, we demonstrated that cuttlefish can smoothly change their pattern to vary with small changes in the background visual features (Fig. 3). Mechanistically, we found that this is accomplished by coordinating groups of chromatophores, with different groups showing positive and negative correlations with background visual features.

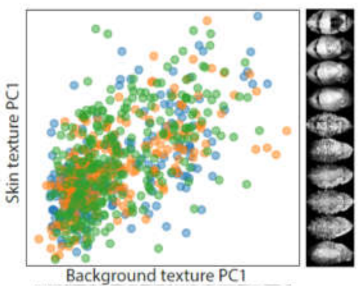


Fig. 3: High correlation between cuttlefish and background visual textures. Colors: N=3 animals

We then turned to the dynamics of camouflage pattern matching. Our own prior work on cuttlefish skin patterning had demonstrated surprisingly simple dynamics during visual threat displays. We expected to observe similar dynamics in the context of camouflage. We were therefore surprised to find that cuttlefish camouflage is characterized by a meandering trajectory through the space of camouflage patterns, with multiple pauses as the animal moves to a final stable pattern (Fig. 4). The switching directions of movement, and the observation that pauses lengthen as the animal approaches a stable pattern suggest that the system employs visual feedback and periodic updating to precisely match the background. The mechanism for such feedback is currently unclear and is a direction for future work.

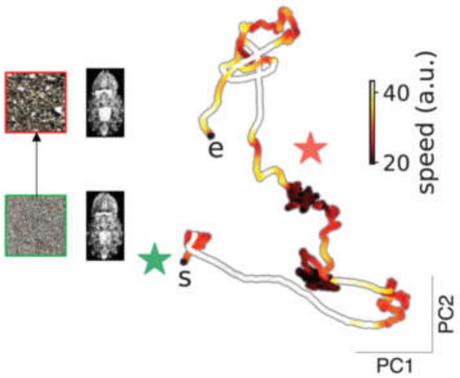


Fig. 4: Meandering, pausing dynamics of cuttlefish camouflage pattern, visualized in the top 2 principal components of visual texture space.

Finally, we turned to look at the implementation of these dynamics at chromatophore resolution. We employed community detection-based clustering to extract groups of co-fluctuating chromatophore 'components'. We found that these components could be spatially overlapping or disjoint, and it is the different component dynamics over a camouflage trajectory that produces the meandering paths in camouflage space we observe at the scale of the entire animal. Interestingly, components appear to reconfigure rapidly, with camouflage trajectories that are similar by eye employing different sets of components. These details, unobservable until now because of lack of resolution, paint a complex picture of the neural basis of camouflage in these animals. They serve as a basis for mechanistic studies of motor control in this remarkable image generation system, whose brains are separated from ours by over 600 million years.

We have submitted a manuscript presenting this project, currently under review.

Woo, T., Liang, X., Evans, D., Fernandez, O., Kretschmer, F., Reiter, S., Laurent, G., Visual texture-matching search in camouflaging cuttlefish. Nature (under review).

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5．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　0件／うちオープンアクセス　0件）

1．著者名 Sam Reiter, Gilles Laurent	4．巻 60
2．論文標題 Visual perception and cuttlefish camouflage	5．発行年 2020年
3．雑誌名 Current Opinion in Neurobiology	6．最初と最後の頁 47-54
掲載論文のDOI（デジタルオブジェクト識別子） 10.1016/j.conb.2019.10.010	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 －

〔学会発表〕　計2件（うち招待講演　2件／うち国際学会　0件）

1．発表者名 Samuel Reiter
2．発表標題 An ecological approach to understanding the brain
3．学会等名 OIST-RIKEN Collaboration 1st Symposium: Green and blue planet -How can ecological research shape our future?（招待講演）
4．発表年 2021年

1．発表者名 Samuel Reiter
2．発表標題 How much and in what ways can behavior tell us about the brain?
3．学会等名 Physics of Behavior Virtual Workshop（招待講演）
4．発表年 2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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6．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考

7．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

共同研究相手国	相手方研究機関