様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

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研究課題名（和文）Somatosensory integration in the Secondary Somatosensory Cortex and its role in the formation of self-body consciousness

研究課題名（英文）Somatosensory integration in the Secondary Somatosensory Cortex and its role in the formation of self-body consciousness

研究代表者

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研究成果の概要（和文）：この実験では、ニホンザルの脳の二次体性感覚野と呼ばれる領域のニューロンを記録しました。この領域のニューロンは視覚と触覚に反応するため、鏡の前でサルに刺激を与えました。手や物体を近づけると、サルがそれらに触ることがなくてもニューロンが反応することを確認しました。これらの反応はサルが鏡を通してしか見えない場合にも生じていました。この結果は、視覚も触覚関連の領域で重要な機能であることを示すこれまでの研究と一致しています。サルが自分の体への刺激を鏡を通して見た場合の反応も、サルが鏡に映った自分のイメージを理解するという、生まれつきではなく学習された能力の直接的な神経の証拠を示しています。

研究成果の学術的意義や社会的意義
This study show neurophysiological evidence of mirror self-recognition that complements previous behavioral studies. These results are important for understanding body-perception psychological disorders and how the concept of a self-body is formed in the brai, a pre-requisite for consciousness.

研究成果の概要（英文）：In this experiment we checked how neurons responded to the self-image in a mirror in macaque monkeys. We recorded a brain region called Secondary Somatosensory Cortex, which function is still not well known. Neurons in this region respond to both touch and visual stimuli, so we stimulated the monkey by touch in front of a mirror.

We found neuronal responses to both touch and vision when the experimenter's hand or an object approached the monkey, even without touching the animal. These responses happened also when the monkey could not directly see the stimuli, but only the mirror image. These results agree with previous studies showing that vision is also an important feature in these mostly touch-related areas. Responses to stimulation to the monkey's own body seen in the mirror also show direct neuronal evidence that macaque are able to recognize their own image in a mirror.

研究分野：Neuroscience

キーワード：secondary somatosensory　s2　sii　consciousness　macaque　monkey　mirror　self recognition

様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９（共通）

１．研究開始当初の背景

Many experiments have proposed behavioral methods to test if an animal can recognize itself in a mirror. The most famous of those is the marker test, in which a colored mark is painted in the face of the animal and, upon exposition to a mirror, the animal should touch their own face where the marker is, indicating the understanding that the mirror image is themselves. Evidence from such a test in Macaque monkeys is controversial, with no clear indication of macaques having the ability of mirror self-recognition.

Neurons in the secondary somatosensory cortex (SII) of macaques have been found to respond to both somatosensory and visual stimuli. Responses in this area are topographically organized, similar to the somatotopic maps in the primary somatosensory cortex, but at the same time being more diffuse, with a more spatially proportional representation. That means, compared to the primary cortex, the SII have a closer representation of the surface area of a body part rather than the number of receptors it contains. Besides that, each neuron may respond to multiple body areas or a large part of the body. These factors suggest this region may have a role in whole-body representation, an important aspect of mirror self-recognition.

２．研究の目的

Our goal with this study is to understand if neurons in the SII respond to the self-image in a mirror. Since macaque do not show innate mirror self-recognition, we want to show if this ability could be acquired through training. Mirror self-recognition could be learned through the combination of both somatosensory and visual stimuli, as it happens in the SII, by associating what is felt in the body to what is seen in the mirror.

The research directly shows responses of SII neurons to different types of touch or approximation in front of the mirror: animal touching or approaching the self, the experimenter, or objects, as well as being touched or approached by the experimenter or objects. In this way, the role of the SII could be better clarified in relation to the source and goal of touch, visual and tactile responses, and how the neuronal response are affected by the mirror image, clarifying the role of the SII.

In the technical aspects, we aim to develop more efficient recording methods through custom made head implants, improving surgical techniques and the comfort for the animal. We are also developing a more efficient method for automatically labeling videos and synchronize stimulation information with neuronal recordings. This method can greatly reduce the amount of manual work required for analyzing behavioral experiments with complex stimulation. With this method, experiments could use stimuli closer to those experienced in more natural conditions without compromising data accuracy or increasing the work necessary for labeling data.

In a broader sense, this study could provide electrophysiological evidence of self-body awareness in the brain. Knowing the biological basis of this process could help understanding consciousness and psychoneurological body perception and recognition disorders, such as autotopagnosia, anorexia nervosa, or body dysmorphia.

３．研究の方法

In this experiment we utilized Japanese macaque (*Macaca fuscata*) as subjects. The monkeys were stimulated in front of a mirror through touch, catching food, and regular movement until showing behavioral indications of mirror self-recognition, such as passing the marker test or touching a light produced by a laser pointer shone in their body after seeing it in the mirror.

The first stage of the experiment, after mirror self-recognition was stablished with training, consisted of the experimenter approaching or touching the animal, or moving the animal's hand so that the animal would touch themselves, an external object, or the experimenter. When necessary, the animal would have their vision blocked so that direct view of the stimuli was not possible, but mirror view (indirect) was still achievable. During this task, neurons in the SII were recorded bilaterally with varnished tungsten electrodes.

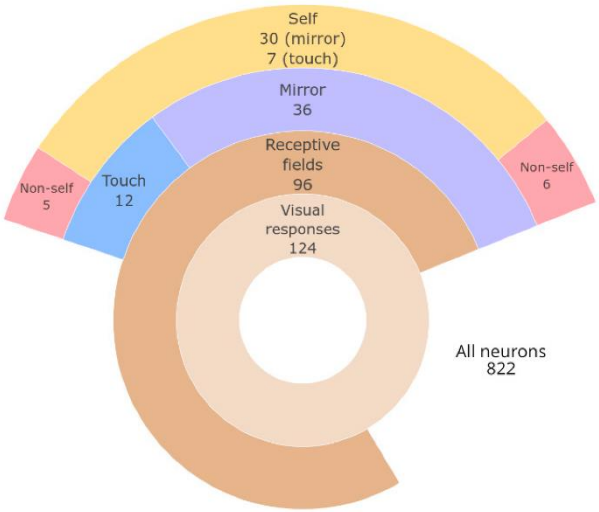
The neuronal responses were evaluated in real-time and cross checked by a second experimenter. Some neurons were recorded along a multi-camera video of the task and manually labeled offline.

In a second stage of the experiment, a method was developed to streamline the labor-intensive process that involved stimulating the animal and labeling the recorded videos. For this, an automatic stimulation system was devised, consisting of a piezoelectric touch-sensor to be freely manipulated by the experimenter. Video of the task was automatically analyzed through deep learning (DeepLabCut, Mathis et al., 2018), with the monkey body parts and their position tagged without human intervention. Furthermore, gaze location was also recorded in 60hz. These three sources of data are integrated using the same timing signal and could be joined with the recorded neuronal activity.

The surgical process was also improved with the development of 3D printed custom implants, made according to each monkey's cranial shape. The implants include in a single piece multiple recording chambers and the fixation piece for the head holder. Being made of biocompatible polymer, the implants intend to reduce the risk of infections in the interface between skin and implant, reduce the number of surgical interventions necessary while making those faster, and improve the comfort for the animal.

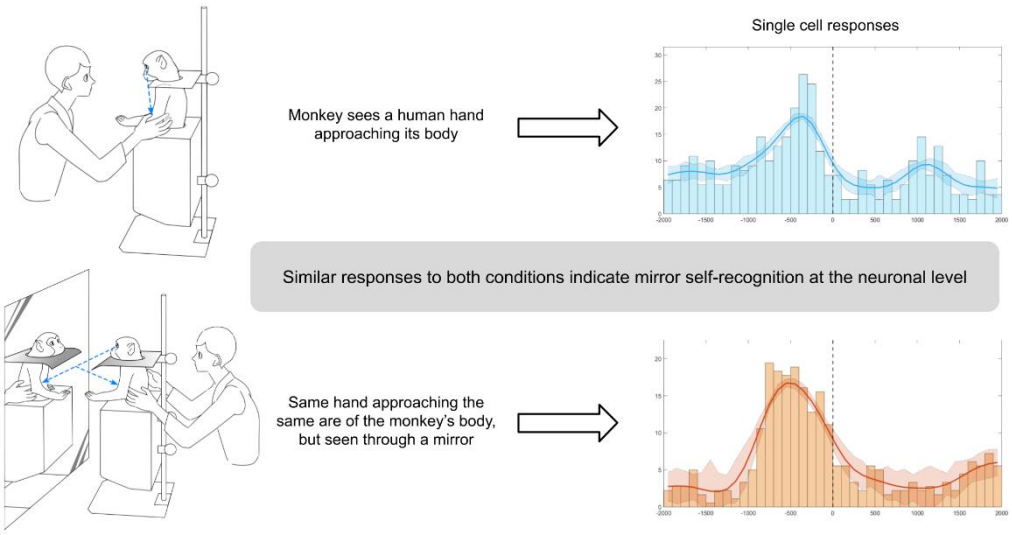
4. 研究成果

Initially, a total of 822 neurons were recorded within the target region in both the right and left hemispheres of one Japanese macaque (*Macaca fuscata*) trained to recognize herself in the mirror. Responses to visual stimuli were detected in 124 units, being divided into two main categories: to the mirror or to touch. Within these, we further subdivided the responses into self-related or non-self-related. That is, neurons that responded when the stimulus was done towards the self (the monkey) or towards an object or the experimenter. This is a visual summary of the responding neurons found:

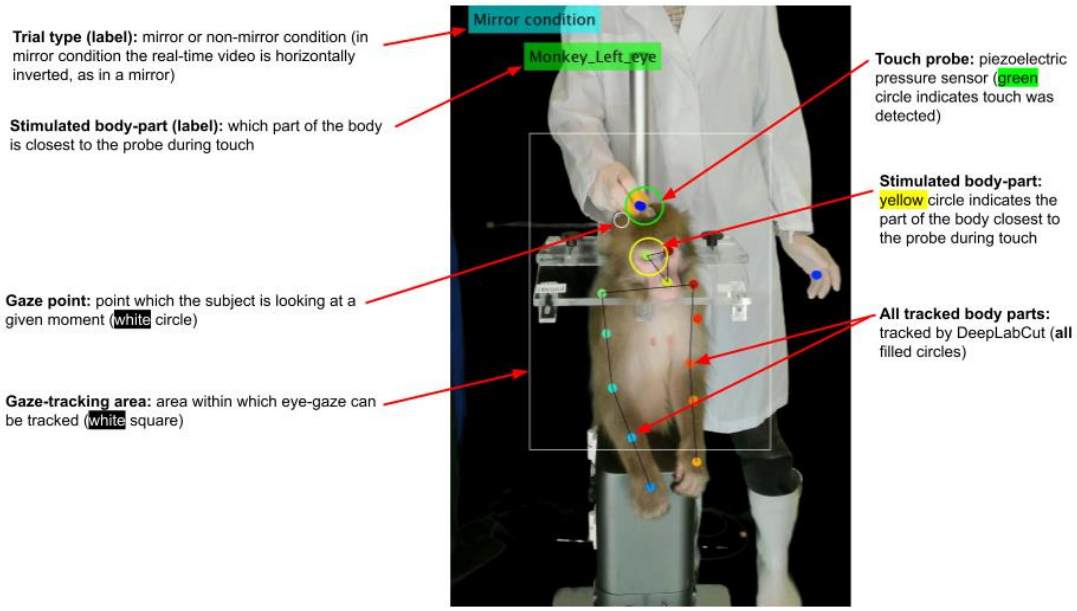


We were able to confirm that neurons in the SII respond to both visual and tactile stimuli, as well as showing differential responses to the self and non-self. We also showed that those responses were stable even when the stimuli could only be seen through the mirror, such as the example illustrated below. This provides direct neuronal evidence of mirror self-recognition in the macaque SII, even when mirror self-

recognition is not innate, but learned.



In the technical side, the method for automated behavioral and neuronal evaluation was developed, showing high precision in automatically synchronizing and labeling the data in the behavioral trials. It allows a single experimenter to focus on stimulating the animal while the location, distance, and timing of the stimulation are automatically tagged and recorded. A trial is only validated if the gaze point coincides with the stimulation location (also automatic). The results are exported as a discrete format for statistical analysis together with visual representations for manual confirmation of the labeling accuracy (example below). This method was not yet used during neuronal recording, but it has been undergoing testing with two other monkeys during mirror self-recognition training.



These results point to a role of the SII in associating somatosensory and visual information, differentiating self and non-self. This could be the mechanism through which a sense of self is developed, a pre-requisite for mirror self-recognition. Therefore, the SII would be situated as a fundamental but rudimentary precursor of consciousness, being one of the early areas in which multisensory information is differentiated into self- and non-self.

５．主な発表論文等

〔雑誌論文〕　計2件（うち査読付論文　2件／うち国際共著　1件／うちオープンアクセス　2件）

１．著者名 Bretas Rafael、Taoka Miki、Hihara Sayaka、Cleeremans Axel、Iriki Atsushi	４．巻 11
２．論文標題 Neural Evidence of Mirror Self-Recognition in the Secondary Somatosensory Cortex of Macaque: Observations from a Single-Cell Recording Experiment and Implications for Consciousness	５．発行年 2021年
３．雑誌名 Brain Sciences	６．最初と最後の頁 157～157
掲載論文のDOI（デジタルオブジェクト識別子） 10.3390/brainsci11020157	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 該当する

１．著者名 IRIKI Atsushi、SUZUKI Hiroaki、TANAKA Shogo、BRETAS VIEIRA Rafael、YAMAZAKI Yumiko	４．巻 63
２．論文標題 THE SAPIENT PARADOX AND THE GREAT JOURNEY: INSIGHTS FROM COGNITIVE PSYCHOLOGY, NEUROBIOLOGY, AND PHENOMENOLOGY	５．発行年 2021年
３．雑誌名 PSYCHOLOGIA	６．最初と最後の頁 151～173
掲載論文のDOI（デジタルオブジェクト識別子） 10.2117/psysoc.2021-B017	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

〔学会発表〕　計2件（うち招待講演　0件／うち国際学会　2件）

１．発表者名 Bretas, R., Taoka, M., Hihara, S., Iriki, A.
２．発表標題 Neural evidence of mirror self-recognition in the Macaque SII and implications for consciousness
３．学会等名 JNSS 2021 Meeting, Kobe, Japan（国際学会）
４．発表年 2021年

１．発表者名 Bretas, R., Taoka, M., Hihara, S., Cleeremans, A., Iriki, A.
２．発表標題 Self-awareness from multisensory integration: neuronal evidence of mirror self-recognition in the Macaque SII
３．学会等名 2021 SFN Meeting. Neuroscience Meeting Planner. Online（国際学会）
４．発表年 2021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