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Towards a systematic turn in cognitive neuroscience.

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Abstract

It sounds like a cliche to point out the importance of seeing the brain as a system. Even so, today we do not understand the essential systems level features that makes it possible for the brain to realize its remarkable functionality, including dynamical adaptability, sensori-motor coordination, conceptualization, and context dependent learning. In this paper, some essential systems level features of the brain are discussed, based on recent neurophysiological evidences. Data from binocular rivalry experiments are presented as a specific instance. Finally, some basic constraints that a systems level brain model should satisfy are proposed.

1. Introduction

There are approximately 100 billion neurons in the brain, each connected to other neurons via thousands of synapses. The strength of these synapses are modified over a wide range of time as the result of the brain development and experience. Brain areas are heterogeneous in the sense of synaptic connectivity and the kind of neurotransmitters involved. In order to understand such a complex system, a reductionist approach, which tries to reduce everything down to the synaptic interaction, is simply not practical. We need to start from a clear and explicit hypothesis on how the brain functions as a system, rather than hoping that somehow brain function would emerge when you put sufficient number of neurons together in a sufficiently complex manner.

It is important to point out at the outset the limit of the approach of localizing the functionality of the cortical areas based on such experimental techniques as single unit recording, fMRI, MEG etc. Even if one cortical area is indicated to carry one particular function, its ultimate functionality must be grounded within the context of the whole brain system.

It is even possible that multiple functionality is imposed on a cortical area. One of the evolutionary constraints on the brain is that the cortical information processing has to be done with limited spatial resources. Accordingly, the brain is likely to have employed the strategy to utilize a single cortical area for multiple purposes. The primary visual cortex (V1) has been traditionally considered to be a typically visual area. Recent evidence has shown that it plays an essential role in judging the orientation of a grating by touch (Zangaladze 1999). It is thus likely that the area V1 functions not only as a primary visual area, but also as the "hub" of spatial information processing, regardless of the sensory modalities, when a precise geometrical information such as orientation, distance, angle etc. are involved. The "body image" area in the parietal cortex, on the other hand, seems to be concerned more with the integral and real-time processing of sensory and motor information, rather than precise geometrical information.

The multiple functionality of a cortical area, as well as other new insights into the brain function revealed by modern cognitive neuroscience (the case of mirror neurons is a particularly striking example, can be only be understood within the systems level property of the brain. There is a systematic turn in cognitive in the making.

2. Sensory and Intentional Qualia

To study the brain function without paying regard to consciousness is like studying the stomach without paying regard to digestion. The subjective, phenomenal properties invoked by the neural activities in the cortex provide important clues to the systems level principles of the brain fucntion. In recent years, qualia (sensory qualities such as the redness of red) have emerged as the central issue in the scientific pursuit of the problem of consciousness (Chalmers 1996).

A subset of neural activities in the brain results in the subject having sensory qualia (such as the redness of red) and intentional qualia (such as the meaning of a word). A growing set of evidences suggests that sensory and intentional qualia arise from a spatially distributed cluster of neural firings, each reflecting different aspects of the systems level property of the brain. The sensory qualia reflect a relatively stable representation of the generic features in the environment. When the subject is presented with a visual stimulus multiple times, he is likely to experience the same set of sensory qualia. On the other hand, the intentional qualia reflect a dynamic, context dependent interpretation of the environment. In the famous “young woman vs old woman” figure (Fig.1), what you perceive in terms of sensory qualia is the spatial distribution of color qualia with varying shades from white though gray to black. On the other hand, the “interpretation” of the figure is bistable. Your interpretation of the picture, which is phenomenally perceived as intentional qualia, switches between the two alternatives. When looking at a “bistable figure” such as this, what we experience is a dynamic matching between sensory qualia and intentional qualia.

Fig.1 Young woman vs Old woman

Based on neurophysiological evidences, it is possible to pin down the neural correlates of these two different kinds of qualia. Sensory qualia, e.g. visual qualia (such as the redness of red) are likely to arise from the cluster of neural acticities starting from the early sensory areas. In vision, neural activity in area V1 is essential in giving rise to sensory qualia (Weiskrantz 1990). Intentional qualia, on the other hand, are likely to arise from the cluster of neural activities within the higher cortical areas. The higher visual areas such as IT, MT give rise to intentional qualia that contribute to the dynamic, context-dependent interpretation of the visual stimulus.

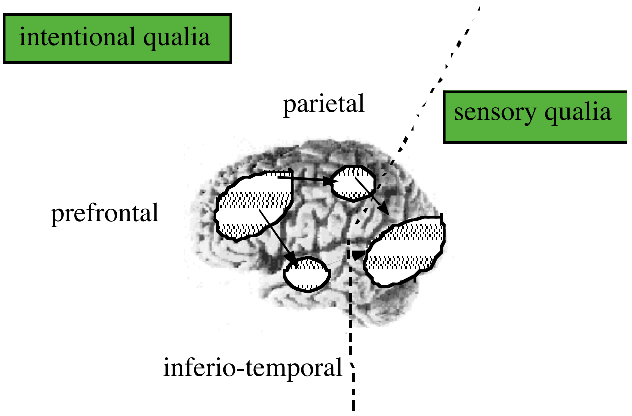

Fig. 2 Sensory and intentional qualia

3. Dynamical Adaptability in Binocular Rivalry.

Binocular rivalry is a striking phenomenon where inputs from the two eyes compete to emerge in visual awareness. For example, when horizontal and vertical gratings are presented to the right and left eye, you see either the horizontal and vertical gratings in the visual field, where the ocular dominance pattern changes with time in a dynamical manner (Fig.3)

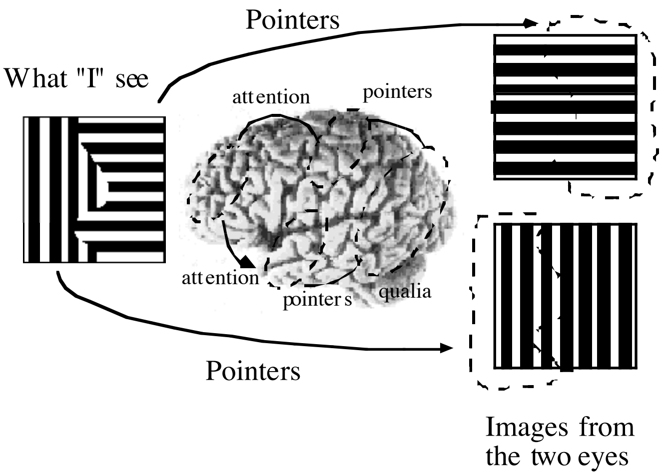

Fig.3 Binocular Rivalry

Recent neurophysiological evidences suggest that binocular rivalry result from the interaction between the "pointers" that correlate with the neural activities in higher visual areas and prefrontal areas, and the sensory qualia that correlate with the neural activities starting from area V1. Here, the pointers are a special form of visual intentional qualia. In order to see something, it seems that it is necessary that there is a "matching" between intentional qualia (in this case termed "pointers") and sensory qualia. What is changing in binocular rivalry is the matching between sensory and intentional qualia.

Taya and Mogi (1999) studied the dynamical adaptability of the matching between pointers and sensory qualia as is evident in binocular rivalry. In this experiment, the image of a circle moving horizontally with a constant velocity in a homogeneous color background was presented to the right and left (Fig.4). The background color was blue for the left eye and yellow for the right eye. There was a phase difference between the motion of the two circles. The resulting color of the background in visual awareness was used as the indicator of the ocular dominance pattern.

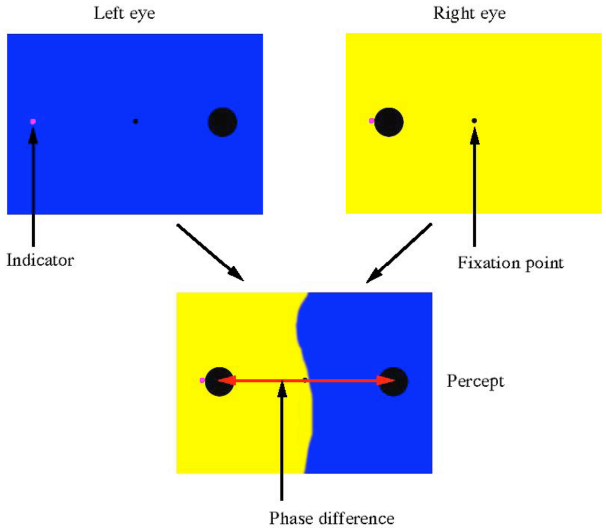

Fig.4 Stimulus of moving circles.

It was found that the spatio-temporal dominance pattern was strongly influenced by the presence of moving circles. The subjects reported that both of the moving circles were always present in visual awareness. The background color perception changed in a manner consistent with the motion of the circles. The percept of a circle was surrounded by the percept of the background color on which the moving circle is presented (ipsilateral color). Subjects reported always seeing both circles in “slower” motions down to ~0.3 degrees per second, and “faster” motions up to ~ 20 degrees per second. When the motion was less than 0.2 degrees per second, sometimes one of the circles disappeared from visual awareness. When two stationary circles were presented in rivalry, sometimes either one or both of them disappeared from the percept (Fig.5).

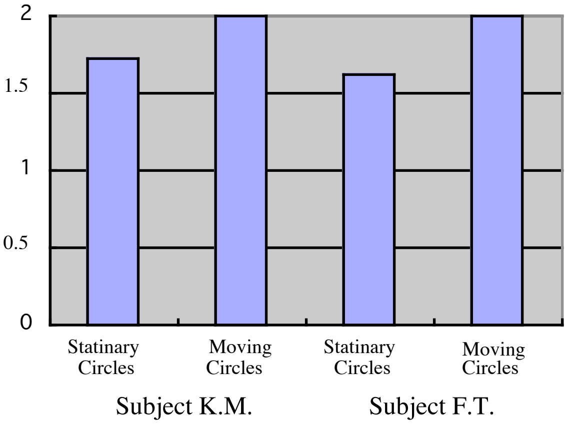

Fig.5 Average number of circles seen.

To facilitate a quantitative analysis, the subjects were requested to report the perceived color at the position of the indicator which appeared as a flashing point in several positions during the course of the movement of the circles. The analysis of the ocular dominance pattern in the spatio-temporal domain shows a strong correlation between the dominance pattern and the position of the moving circles. Figure 5 shows the probability of perceiving the ipsilateral color as the function of the distance between the indicator and the center of the moving circles. The probability of seeing the ipsilateral color is large when the distance between the indicator and the circle is small. The tendency to see the ipsilateral color in the vicinity of a circle (vicinity effect) is less evident when the circles are in stationary positions. This tendency is most pronounced when the phase difference = 180 degrees (i.e., when the circles are moving in counter-phase), and disappears when the phase difference = 0 (i.e., when the circles are moving together, as a single circle in effect). These data indicate that the perceived background color (and therefore the ocular dominance pattern) changes in such away that both of the moving circles are present in visual awareness.

Thus, the motions of the circles count as salient features, influencing what we see consciously. The ocular dominance pattern must change in such a way that both of the moving circles are always present in visual awareness. The visual system behaves as a dynamically adaptive system to make such a percept change possible.

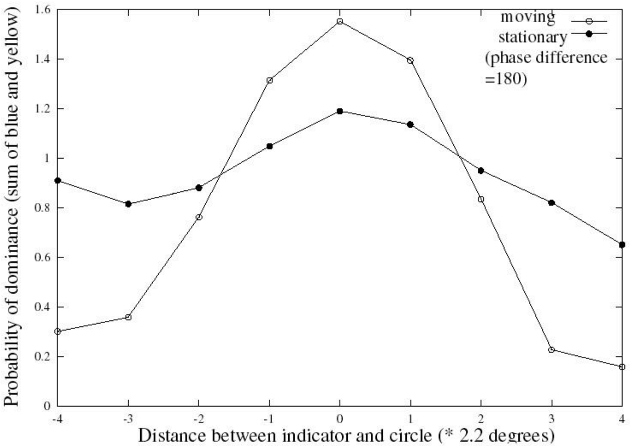

Fig.6 `Probability of dominance of background color

4. The Significance of Noise.

Area MT is considered to be the center of motion information processing in vision. Only about 30% of the variability of neural activities in area MT can be accounted for by the variability of the motion signal itself (Mogi and Barlow 1999). This can be shown by calculating the efficiency of signal detection based on the responses of MT neurons (Fig. 7), where efficiency is defined as the ratio

<external noise> / <internal noise> + <external noise>.

Here, the internal noise represents the variability inherent in neural network, and external noise represents the variability in the stimulus itself.

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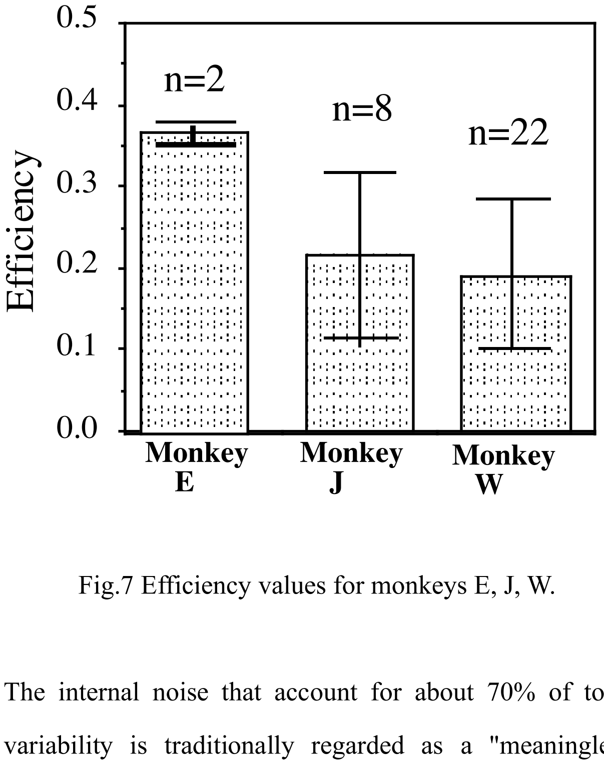

Fig.7 Efficiency values for monkeys E, J, W.

The internal noise that account for about 70% of total variability is traditionally regarded as a "meaningless noise". There is a surprisingly high degree of noise in the neural activities in the cortex. It is sometimes argued that the brain is constructed in such a way that it functions robustly under the presence of a high level of noise, whereas a digital computer would malfunction by the occurrence of even a single bit of noise. However, from a systems level viewpoint, especially keeping the "multiple uses of a single cortical area" idea (see Zangaladze et. al. 1999) in mind, the large variability of neural activities in area MT could be seen to carry information reflecting alternative contexts other than motion signal processing. One possibility is that the variability is closely coupled with the dynamical adaptability of the visual system, as is suggested by the experiment on binocular rivalry (Taya and Mogi 1999).

When we define the noise in the neural system, we only do so in reference to the most apparent stimulus feature that the neurons selectively respond to. In this paradigm, any variability in neural activities that do not directly correspond to that feature would be automatically discarded as “noise”. However, it is quite possible that the variability in neural activities actually reflects some contexts other than the stimulus feature. If this is the case, the variability of neural activity is not a meaningless noise. It rather reflects the multiple contexts within which the neurons in a particular cortical area become functional. In order to understand the properties of neural activities in this respect, it is necessary to take a systems point of view, which has been largely lacking in neuroscience up to today.

5. Conclusion.

Based on the above arguments and other recent evidences from neuroscience, the following ideas for understanding the systems level properties of the brain are suggested.

(1) One of the evolutionary pressures on brain function has been the limitation on spatial resources. The brain has therefore likely to have adapted the strategy of using a single cortical area for multiple purposes.

(2) The neural activity in single cortical area would reflect multiple contexts. This could account for the high level of the variability of neural activity as measured by the traditional definition in which any variability that cannot be explained by the stimulus feature itself is discarded as noise.

(3) In understanding the systems level properties of brain function, the phenomenal (first person) aspects of perception provide important clues. In particular, the distinction between sensory and intentional qualia and their neural correlates provide a good paradigm.

(4) The sensory qualia provide a relatively stable representation of the environment. The intentional qualia represent a dynamic, context-dependent interpretation of the environment.

(5) In cases as binocular rivalry, there is a dynamical interaction between sensory and intentional qualia. Vision is an active process, where the external inputs are matched with internal models.

(6) In the formation of body image (e.g., Iriki et al. 1996), the interaction between sensory and motor information is important. The resulting body image is phenomenologically perceived as a form of intentional qualia, reflecting the multiple contexts necessary for the execution of appropriate motor activities in interacting with the environment.

6. References

Chalmers, D. (1996) The Conscious Mind. Oxford university Press.

Iriki, A., Tanaka, M,. and Iwamura, Y. (1996) Coding of modified body shema during tool use by macaque postcentral neurons. *Neuroreport* **7**, 2325-2330/

Mogi, K. Response Selectivity, Neuron Doctrine, and Mach's Principle. in Riegler, A. & Peschl, M. (eds.) Understanding Representation in the Cognitive Sciences. New York: Plenum Press. 127-134. (1999)

Mogi, K & Barlow, H B. The source of variability in neural responses from MT. J.Physiol 515, pp. 101-102 (1999)

Taya, F. & Mogi, K. Feature induced spatiotemporal structure in binocular rivalry. Perception 28 Supplement pp.135 (1999).

Zangaladze, A. et al. INVOLVEMENT OF VISUAL CORTEX IN TACTILE DISCRIMINATION OF ORIENTATION. Nature 401, 587 - 590 (1999)

Weiskrantz, L. (1990) Blindsight. Oxford University Press.

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