Prefrontal cortex and decision-making:

How does delay-period activity contribute to the decision of the saccade direction?

Shintaro Funahashi

Kokoro Research Center
Kyoto University
Sakyo-ku, Kyoto 606-8501, Japan.
Cerebral cortex of rhesus monkey

Central sulcus
Arcuate sulcus
Lateral sulcus
Principal sulcus
Prefrontal cortex and decision making

A. Characteristics of delay-period activity

B. *How does delay-period activity contribute to the decision of saccade directions?*
**ODR task and task-related prefrontal activity**

**Oculomotor delayed-response (ODR) task**

- **Intertrial interval**
- **Fixation point**
- **Fixation period** (1.0 s)
- **Visual cue**
- **Cue period** (0.5 s)
- **Delay period** (3.0 s)
- **Eye movement**
- **Response period** (Max 0.4 s)

**Examples of task-related activity**

- **Cue-period activity**
- **Delay-period activity**
- **Response-period activity**
Delay-period activity in the prefrontal cortex

Examples of task-related activity

Cue-period activity

Delay-period activity

Response-period activity

Directional delay-period activity

Population vector analysis of prefrontal activities

A. Directional delay-period activity

B. Tuning curves of delay-period activity

C. Polar plots of preferred directions

Prefrontal cortex and decision making

A. Characteristics of delay-period activity
   1. Many prefrontal neurons exhibited delay-period activity.
   2. Most of delay-period activity showed directional selectivity.
   3. Response characteristics of delay-period activity suggest that this activity is a neural correlate of the mechanism for temporarily maintaining information.

B. How does delay-period activity contribute to the decision of saccade directions?
Prefrontal cortex and decision making

A. Characteristics of delay-period activity
   1. Many prefrontal neurons exhibited delay-period activity.
   2. Most of delay-period activity showed directional selectivity
   3. Response characteristics of delay-period activity suggest that this activity is a neural correlate of the mechanism for temporarily maintaining information.
   4. **What information does delay-period activity represent?**
**ODR task and rotatory ODR (R-ODR) task**

**ODR task**

- Intertrial interval

**R-ODR task**

- Monkeys need to make a saccade 90° clockwise from the cue direction

- Fixation period (1.0 s)

- Cue period (0.5 s)

- Delay period (3.0 s)

- Response period (Max 0.4 s)

---

Delay-period activity representing the visual cue location

ODR task

R-ODR task

C: cue period (0.5s)
D: delay period (3 s)
R: response period

What information is maintained in prefrontal activity?

Examples of task-related activity

Cue-period activity

Delay-period activity

Response-period activity


Activity representing visual cue location

Activity representing saccade direction
Prefrontal cortex and decision making

A. Characteristics of delay-period activity

1. Many prefrontal neurons exhibited delay-period activity.
2. Most of delay-period activity showed directional selectivity.
3. Response characteristics of delay-period activity suggest that this activity is a neural correlate of the mechanism for temporarily maintaining information.
4. Delay-period activity maintains either retrospective or prospective information.
Prefrontal cortex and decision making

A. Characteristics of delay-period activity
   1. Many prefrontal neurons exhibited delay-period activity.
   2. Most of delay-period activity showed directional selectivity.
   3. Response characteristics of delay-period activity suggest that this activity is a neural correlate of the mechanism for temporarily maintaining information.
   4. Delay-period activity maintains either retrospective or prospective information.

1. Directional delay-period activity participates in sensory-to-motor information processing.
2. This sensory-to-motor information processing is related to the establishment of the saccade direction in the response period.
Prefrontal cortex and decision making

A. Characteristics of delay-period activity

1. Many prefrontal neurons exhibited delay-period activity.
2. Most of delay-period activity showed directional selectivity
3. Response characteristics of delay-period activity suggest that this activity is a neural correlate of the mechanism for temporarily maintaining information.
4. Delay-period activity maintains either retrospective or prospective information.

1. Directional delay-period activity participates in sensory-to-motor information processing.
2. This sensory-to-motor information processing is related to the establishment of the saccade direction in the response period.

Directional delay-period activity may participate in the decision process of the saccade direction.
Prefrontal cortex and decision making

A. Characteristics of delay-period activity
   1. Many prefrontal neurons exhibited delay-period activity.
   2. Most of delay-period activity showed directional selectivity.
   3. Response characteristics of delay-period activity suggest that this activity is a neural correlate of the mechanism for temporarily maintaining information.
   4. Delay-period activity maintains either retrospective or prospective information.

B. How does delay-period activity contribute to the decision of the saccade direction?
**ODR task and S-ODR task**

**ODR task**
- Intertrial interval
- **Fixation point**
  - Fixation period (1.0 s)
- **Visual cue**
  - Cue period (0.5 s)
- **Delay period** (3.0 s)
- **Eye movement**
  - Response period (Max 0.4 s)

**S-ODR (self-selection ODR) task**
- Monkeys need to make a saccade toward any one of 4 cue directions

Monkeys need to make a saccade toward the direction of the visual cue

**Behavioral analysis**

- Comparison of saccade reaction times between ODR and S-ODR tasks
  
  ODR task: $286.0 \pm 40.3$ (SD) ms (14216 trials)
  
  S-ODR task: $301.3 \pm 45.7$ (SD) ms (16960 trials)

- Comparison of saccade reaction times between preferred directions and non-preferred directions in the S-ODR task
  
  Preferred direction: $305.6 \pm 44.6$ (SD) ms (5695 trials)
  
  Non preferred direction: $303.3 \pm 46.4$ (SD) ms (1887 trials)

---

**Behavioral analysis**

- Comparison of saccade reaction times between ODR and S-ODR tasks
  
  **ODR task:** 286.0 ± 40.3 (SD) ms (14216 trials)
  
  **S-ODR task:** 301.3 ± 45.7 (SD) ms (16960 trials)

- Comparison of saccade reaction times between preferred directions and non-preferred directions in the S-ODR task
  
  **Preferred direction:** 305.6 ± 44.6 (SD) ms (5695 trials)
  
  **Non preferred direction:** 303.3 ± 46.4 (SD) ms (1887 trials)

Saccade reaction times were not significantly different between ODR and S-ODR tasks.

The monkey made the decision of the saccade direction before the GO signal presentation in the S-ODR task.

Which task-related activity contributes to the decision of the saccade direction in the S-ODR task?

Examples of task-related activities

- **Cue-period activity**

- **Delay-period activity**

- **Response-period activity**
An example of prefrontal activity in ODR and S-ODR tasks

Comparison of task-related activity between ODR and S-ODR tasks

Temporal pattern of directional delay-period activity

Population histograms using all directional delay-period activities recorded

(A) ODR task

(B) S-ODR task

Temporal change of the strength of Directional selectivity (ROC values)

Watanabe & Funahashi (2007): Cerebral Cortex 17: i88-i100.
Which task-related activity contributes to the decision of the saccade direction in the S-ODR task?

**Examples of task-related activities**

**During ODR performances**

- **Cue-period activity**
  
  
  
  
  Either cue-period activity is not observed or omni-directional cue-period activity is observed.

- **Delay-period activity**
  
  
  
  
  1. Directional delay-period activity is observed with similar directional selectivity as is observed in the ODR task.
  2. The strength of the directional selectivity increases gradually during the delay period.

- **Response-period activity**
  
  
  
  

**Task-related activities**

**During S-ODR performances**

Watanabe & Funahashi (2007): Cerebral Cortex 17: i88-i100.
Which task-related activity contributes to the decision of the saccade direction in the S-ODR task?

Examples of task-related activities

During ODR performances

Cue-period activity

Delay-period activity

Response-period activity

Task-related activities

During S-ODR performances

Either cue-period activity is not observed or omni-directional cue-period activity is observed.

1. Directional delay-period activity is observed with similar directional selectivity as is observed in the ODR task.

2. The strength of the directional selectivity increases gradually during the delay period.

Directional delay-period activity seems to contribute to the decision of the saccade direction in the S-ODR task.

Watanabe & Funahashi (2007): Cerebral Cortex 17: i88-i100.
Which delay-period activity contributes most to the decision of the saccade direction in the S-ODR task?

1. The temporal pattern of directional selectivity of delay-period activity is different among neurons.
2. The temporal pattern of delay-period activity at the best direction is different among neurons.
   (e.g., tonic sustained, gradually increasing, gradually decreasing, tonic suppressed)

Watanabe & Funahashi (2007): Cerebral Cortex 17: i88-i100.
Temporal pattern of directional selectivity of delay-period activity

1. The 3 sec delay period was divided into three 1 sec periods (D1, D2, and D3 periods).
2. The presence of directional selectivity or not for each 1 sec period was examined by ANOVA.
3. If directional selectivity was present, “1” was assigned for that period. If directional selectivity was not present, “0” was assigned for that period.

An example of (1,1,1) type

An example of (1,0,0) type

Watanabe & Funahashi (2007): Cerebral Cortex 17: i88-i100.
Which delay-period activity contributes most to the decision of the saccade direction in terms of the temporal pattern of the directional selectivity?

Table 1
Number of neurons that exhibited directional selectivity during at least one delay epoch in the S-ODR task, among neurons showing 7 patterns of directional selectivity in the ODR task

| Patterns | Number of neurons | S-ODR task directionally selective | Mean difference | |MDODR–MDS-ODR|<45° |
|----------|-------------------|-----------------------------------|-----------------|-----------------|-----------------|
| (1, 1, 1) | 16 | 12 (75%) | 18.1° | 12 (75%) |
| (1, 0, 1) | 5 | 1 (20%) | 11.5° | 1 (20%) |
| (0, 1, 1) | 11 | 3 (27%) | 30.4° | 2 (18%) |
| (0, 0, 1) | 34 | 8 (24%) | 48.4° | 5 (15%) |
| (0, 1, 0) | 21 | 4 (19%) | 107.3° | 1 (5%) |
| (1, 0, 0) | 29 | 5 (17%) | 99.0° | 1 (3%) |
| (1, 1, 0) | 8 | 1 (12%) | 152.9° | 0 (0%) |

Watanabe & Funahashi (2007): Cerebral Cortex 17: i88-i100.
Which delay-period activity contributes most to the decision of the saccade direction in terms of the temporal pattern of the directional selectivity?

Table 1

Number of neurons that exhibited directional selectivity during at least one delay epoch in the S-ODR task, among neurons showing 7 patterns of directional selectivity in the ODR task

| Patterns | Number of neurons | S-ODR task | Mean difference | |MDODR–MDS-ODR| |
|----------|-------------------|------------|----------------|------------------|-----------------|
| (1, 1, 1) | 16 (75%) | 12 | 18.1° | 12 (75%) |
| (1, 0, 1) | 5 | 1 | 11.5° | 1 (20%) |
| (0, 1, 1) | 11 | 3 | 30.4° | 2 (18%) |
| (0, 0, 1) | 34 | 8 | 48.4° | 5 (15%) |
| (0, 1, 0) | 21 | 4 | 107.3° | 1 (5%) |
| (1, 0, 0) | 29 | 5 | 99.0° | 1 (3%) |
| (1, 1, 0) | 8 | 1 | 152.9° | 0 (0%) |

Neurons exhibited the \( (1,1,1) \) pattern of directional selectivity seem to contribute most to the decision of the saccade direction in the S-ODR task.

Watanabe & Funahashi (2007): Cerebral Cortex 17: i88-i100.
Temporal patterns of delay-period activity in the ODR task

Watanabe & Funahashi (2007): Cerebral Cortex 17: i88-i100.
Temporal patterns of delay-period activity in the ODR task

Which temporal pattern of delay-period activity contributes most to the decision of the saccade direction in the S-ODR task?

Watanabe & Funahashi (2007): Cerebral Cortex 17: i88-i100.
Temporal patterns of delay-period activity in ODR and S-ODR tasks

Gradually increasing (Type A)

Central bank (Type B)

Gradually decreasing (Type C)

Central hollow (Type D)

ODR task

S-ODR task

(sp/s) vs Time from the onset of the delay period

Best direction
Worst direction
Temporal patterns of delay-period activity in ODR and S-ODR tasks

Gradually increasing (Type A)

Central bank (Type B)

Gradually decreasing (Type C)

Central hollow (Type D)

Neurons exhibiting gradually increasing type of delay-period activity seem to contribute the decision of the saccade direction in the S-ODR task.
Which delay-period activity contributes most to the decision of the saccade direction in the S-ODR task?

1. Difference of the temporal pattern of delay-period activity at the best direction among neurons. (e.g., tonic sustained, gradually increasing, gradually decreasing, tonic suppressed)

   **Neurons exhibiting gradually increasing type of delay-period activity seem to contribute the decision of the saccade direction in the S-ODR task.**

2. Difference of the temporal pattern of directional selectivity in delay-period activity at the best direction among neurons

   **Neurons exhibited the (1,1,1) pattern of directional selectivity seem to contribute most to the decision of the saccade direction in the S-ODR task.**
Which delay-period activity contributes most to the decision of the saccade direction in the S-ODR task?

1. Difference of the temporal pattern of delay-period activity at the best direction among neurons. (e.g., tonic sustained, gradually increasing, gradually decreasing, tonic suppressed)

Neurons exhibiting gradually increasing type of delay-period activity seem to contribute the decision of the saccade direction in the S-ODR task.

2. Difference of the temporal pattern of directional selectivity in delay-period activity at the best direction among neurons

Neurons exhibited the (1,1,1) pattern of directional selectivity seem to contribute most to the decision of the saccade direction in the S-ODR task.

What signal or mechanism triggers to initiate particular types of delay-period activity at the beginning of the delay period in the S-ODR task?
Activation at the beginning of the delay period in the S-ODR task

1. Similar magnitude of activation was observed at the beginning of the delay period in the S-ODR task, regardless of the direction of the saccade at the response period.

2. When the monkey eventually made a saccade toward the neuron’s best direction, the activity gradually increased toward the response period.

3. When the monkey eventually made a saccade toward the neuron’s worst direction, the activity gradually decreased during the delay period.
Hypothesis:

“The direction of the saccade is generated by the competitive interactions among neurons having different directional preference.”

1. At the beginning of the delay period, all neurons having different directional preference simultaneously become active.
2. Competitive interactions occur among neurons having different directional preference because of the presence of mutual inhibitory connections among neurons.
3. The winner of this competitive interaction gradually increases the activity toward the response period, whereas the looser decreases the activity.
**Competitive interaction hypothesis**

1. At the beginning of the delay period, all neurons having different directional preference simultaneously become active.
2. Competitive interactions occur among neurons having different directional preference because of the presence of mutual inhibitory connections among neurons.
3. The winner of this competitive interaction gradually increases the activity toward the response period, whereas the looser decreases the activity.

- **Winner**
  - Faster timing of activation
  - Bigger magnitude of activation

- **Looser**
  - Slower timing of activation
  - Weaker magnitude of activation
Determination of the initiation timing of delay-period activity

**Raster displays**

**Raster display and spike density function of one trial**

Distribution of the initiation timing of delay-period activity

Determination of the initiation timing of delay-period activity
A comparison of the initiation timing of delay-period activity between ODR and S-ODR tasks

**ODR task**

- **C**: Cue period
- **D**: Delay period
- **R**: Response period

**S-ODR task**

- **C**: Cue period
- **D**: Delay period
- **R**: Response period

**Initiation timing of delay-period activity**

- **Best direction**
- **Worst direction**
Distribution of the initiation timing of delay-period activity

The onset of the visual cues

The onset of the visual cues
Temporal pattern of the initiation timing of delay-period activity

Cumulative histogram of the initiation timing of delay-period activity

Population average of delay-period activity

Neuron’s best direction (733 trials)

Neuron’s worst direction (616 trials)
**Competitive interaction hypothesis**

1. At the beginning of the delay period, all neurons having different directional preference simultaneously become active.
2. Competitive interactions occur among neurons having different directional preference because of the presence of mutual inhibitory connections among neurons.
3. The winner of this competitive interaction gradually increases the activity toward the response period, whereas the looser decreases the activity.
Inter-trial interval

Neuron population A

Inhibitory interaction

Neuron population B

Neuron population C

Neuron population D
Cue period

Neuron population A

Inhibitory interaction

Neuron population B

Neuron population C

Neuron population D

Cue period
Cue period

Neuron population A

Inhibitory interaction

Neuron population B

Neuron population C

Neuron population D

Cue period
Activation of inhibitory interaction

Neuron population A

Neuron population B

Neuron population C

Neuron population D
Delay period

Neuron population A

Activation of inhibitory interaction

Neuron population B

Neuron population C

Neuron population D

Delay period
Delay period

Activation of inhibitory interaction

Neuron population A

Neuron population B

Neuron population C

Neuron population D

Delay period
Response period

Activation of inhibitory interaction

Neuron population A

Neuron population B

Neuron population C

Neuron population D

Response period
Cue Delay Response

Discharge rate (spikes/s)

sensory processing → decision → working memory (motor set) → execution
Prefrontal cortex and decision making

A. Characteristics of delay-period activity
   1. Many prefrontal neurons exhibited delay-period activity.
   2. Most of delay-period activity showed directional selectivity.
   3. Response characteristics of delay-period activity suggest that this activity is a neural correlate of the mechanism for temporarily maintaining information.
   4. Delay-period activity maintains either retrospective or prospective information.

B. How does delay-period activity contribute to the decision of saccade directions?
   1. Delay-period activity which exhibited stronger magnitude of activity and stronger directional selectivity from the early phase of the delay period in the ODR task plays an important role in the decision of the saccade direction in the S-ODR task.
   2. Competitive interactions occur among neurons having different directional preference because of the presence of mutual inhibitory connections among neurons.
   3. The winner of this competitive interaction gradually increases the activity toward the response period, whereas the looser decreases the activity.
Collaborators

Kyoto University

Kei Watanabe
Motoaki Nitta
Akio Tanaka
Jorge Mario Andreau
Mika Takebayashi

Saori Igaki
Kazuyoshi Takeda
Yumiko Watanabe
Satoe Ichihara-Takeda