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Meaning of gamma distribution in perceptual rivalry

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Perceptual rivalry, which implies binocular rivalry and ambiguous figure perception, is characterized by perceptual alternation between two stable interpretations of an unchanging stimulus. It is well known that the time intervals of alternation follow a gamma distribution (GD) commonly in various kinds of perceptual rivalry. A critical question is whether the GD reflects some general mechanism of this phenomenon. In quantitative investigations of distributions of the alternation intervals, we found that a shape-determining parameter α of GD took a natural number, indicating that the alternation is caused by a discrete stochastic process of the brain. In an extended version of the same experiment, we confirmed that the same property was obtained for each of the various kinds of stimuli. Therefore it is concluded that the GD reflects the general mechanism of perceptual rivalry, that is, the discrete stochastic process underlying perceptual alternation.

Keywords: binocular rivalry, ambiguous figure, visual consciousness, perceptual alternation, stochastic process, gamma distribution.

Introduction

In observing an ambiguous figure such as the Necker cube, we experience spontaneous alternations between two possible percepts of the figure. Similar perceptual alternation is experienced with binocular rivalry, in which incongruent images presented to the two eyes compete to be consciously perceived. It is a common nature of these two kinds of phenomena that the conscious percept of the unchanging stimulus spontaneously alternates. In phenomenology of perceptual alternation, we have a well-known empirical proposition such that the intervals of the alternation follow a gamma distribution (GD) in both binocular rivalry (e.g., Levelt, 1967; Blake, Fox & McIntyre, 1971) and ambiguous figure perception (Borsellino et al., 1972). Thus an important question here is whether the GD reflects some general mechanism of perceptual alternation observed in the various kinds of perceptual rivalry.

In the first experiment we investigated GDs fitted to the alternation intervals of six kinds of perceptual rivalry. A GD is determined by two parameters, α and β, both of which can be any positive real number, and we found that the shape-determining parameter α of the GDs took a natural number such as 1, 2, 3, or 4. Since a GD with α of a natural number is derived from a discrete stochastic process called a Poisson process, this results indicated that perceptual alternation is caused by this kind of stochastic process.

Because of an insufficient number of subjects for each kinds stimulus, however, the first experiment could not show whether this mechanism is common to various kinds of perceptual rivalry. In the second experiment, we had the same 91 subjects for each of seven kinds of rivalrous stimuli, to obtain the statistics of rivalry-fitted GDs of each stimulus. The results showed that the parameter α of the GD took natural numbers for each of all the investigated stimuli, although the sharpness of the α histogram peaks at natural numbers varied among the stimuli. Control trials showed that such a discrete nature could be observed only during the observation of rivalrous stimuli, not by mimicking fluctuations of reports. Thus this discrete stochastic mechanism seems to be general to various kinds of perceptual rivalry.

In the third experiment, we investigated distributions of α of individual subjects, and found that one subject tended to have the same α value regardless of kind of rivalry.

From these results, it is concluded that the discrete stochastic process is a general mechanism of perceptual rivalry. It is the most probable in the present results that the number of the discrete steps is intrinsic to an individual subject.

Experiment 1

Method

Participants. All subjects were recruited from the academic environment of Kanazawa Institute of Technology, and gave written informed consent to participate in the experiments. Each subject had normal or corrected-to-normal vision.

Stimuli and Design. The following six kinds of rivalrous stimuli were used (Figure 1a-f): a binocularly rivalrous stimulus (BR), a bistable apparent motion stimulus (AM), Rubin's vase and faces (RU), Boring's young/old woman (BO), the Necker cube (NC) and a biased version of the Necker cube (BN). Visual stimuli with a fixation point were presented on a CRT monitor, subtending 2 to 4 degrees of arc (depending on stimulus) with a luminance of 3 cd/m^2, in a dark soundproof room. For the BR stimulus, eye prisms and additional occluders assured that the two images were seen convergently. The AM stimulus consisted of two frames of diagonally positioned white disks presented alternately with an SOA (stimulus onset asynchrony) of 133 ms. Vertical or horizontal shuttle motion of the disks were perceived, while other kinds of motion such as rotation were rarely perceived with this SOA.

Twenty subjects (21-33 years) participated in the experiments of BR, NC, and BN. Eighteen subjects (21-32 years) participated in the ones of RU, BO, and AM. The subjects were instructed to touch a percept-assigned electrode of a finger-touching device according to their current percept, and to move the finger quickly to the other when their dominant percept alternated. The finger removal caused the changes of amplified electrical signals, which were sampled at 100 Hz. Time periods between successive finger removals gave us inter-alternation intervals. Before the experiment, the subjects were informed of the two possible percepts of the figure, and had a 15-min practice session, which made their perceptual alternation reach a steady phase. The subjects were asked to assume a passive attitude during their observations, without making any effort to stay at or change their current percept, and also not to move their eyes freely but to use the fixation point. To keep the subjects' judgments simple, the finger movement was required only when the spatial dominance of the percept alternated and not when the percept became partially mixed or vague. For each figure, one hour of observation was comprised of ten 6-min sessions with breaks, during which a substantial number of alternations, approximately 700 alternations on average, were reported.

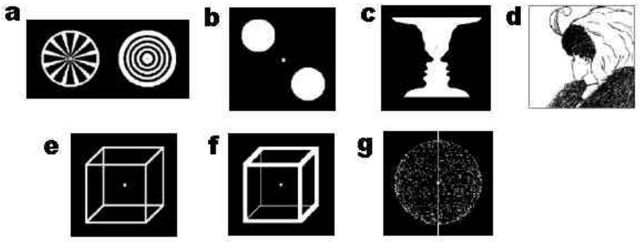

Figure 1. Stimuli of rivalrous figures. (See text for the following abbreviations.) (a) BR. (b) AM. (c) RU. (d) BO. (e) NC. (f) BN. (g) RS.

Data Analysis (Gamma Distribution Fitting). A GD of interval t (s) is defined as follows:

$$f_G(t) = \frac{b^a t^{a-1} e^{-bt}}{\Gamma(a)} \qquad (1)$$

where α (dimensionless) and β (s^{-1}) are positive real numbers, and Γ is the gamma function with argument α.. We calculated numerically the cumulative GD using the Simpson formula and the Maclaurin expansion of the gamma function with a precision of 9 digits in the sweeping ranges of $0.6 \leqq \alpha \leqq 25.0$ and $0.01 \leqq \beta(s^{-1}) \leqq 25.0$. The GD was optimally fitted to the experimentally obtained intervals of each percept by each subject, by minimizing the chi-square statistic. In a coarse-to-fine search of α and β in the ranges above, the optimal GD fitting was uniquely determined with precisions of 10^{-3} and 10^{-4} for α and β, respectively.

Results and Discussion

In more than 80% of the data sets the GDs were not rejected in the chi-square goodness-of-fit test ($p < 0.05$), showing that the GDs provided good fits to the alternation intervals in all the kind of percept. The kind of percept did not have any significant effect on the value of α (Kruskal-Wallis test, $p = 0.35$). A histogram for α, which includes αs pooled for all the percepts, showed distinct peaks at the natural numbers: 2, 3, and 4 (Figure 2a). (Histogram peaks at natural numbers larger than 4 is not clear because of the low frequencies of data points. A possible peak at α = 1 is discussed later.) This result of α being natural numbers provides a crucial clue to the mechanism of perceptual alternation. Because a GD defined by a natural number α is given by the waiting time for discrete stochastic events to occur α times, as explained above, the result suggests that the perceptual alternation was caused by such a discrete stochastic process (Figure 3).

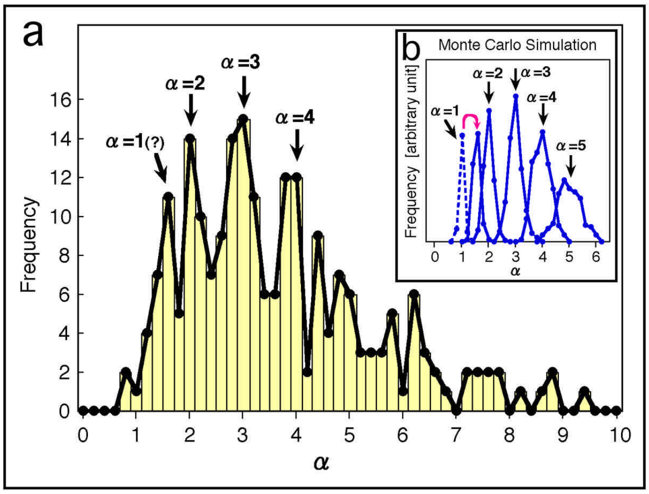

Figure 2. (**a**) Histogram for α obtained in the human experiment, which includes 227 values. (**b**) Histogram for α obtained by Monte Carlo simulation of Poisson processes. The height of each graph was arbitrarily adjusted. The position of the distribution for α = 1 (drawn by the dotted line) was shifted rightward as a result of removing short intervals as indicated by the curved arrow, suggesting a possible positional shift of the α peak in the case of α = 1 (see text).

To test this idea, we had Monte Carlo simulations of Poisson processes, in which discrete stochastic events were simulated to occur using computer-generated random numbers and time intervals until the αth event were calculated. The same algorithm of fitting of GD as in the human experiment was applied to the simulated intervals. As results, we obtained the very similar shapes of the α distributions at 2, 3, and 4 in the simulation (Figure 2b) and the human experiment (Figure 2a), supporting the validity of the proposed stochastic mechanism. Regarding $\alpha = 1$, a special situation must be considered. A GD with $\alpha = 1$ is mathematically equivalent to a decreasing exponential distribution in which shorter intervals occur more frequently. In this case, it seems that human subjects cannot report intervals shorter than their reaction time of finger movements. To estimate the effect of this limitation, we removed intervals shorter than the possible human reaction time (e.g. 280 ms in this simulation) from the sets of simulated intervals of $\alpha = 1$. This removal of short intervals shifted the α peak from 1.0 to 1.6 (as indicated by the curved arrow in Figure 2b) where a peak was observed in the human experiment (Figure 2a). This result suggests that there might be perceptual alternation with $\alpha = 1$ as well as 2, 3, and 4, but that the experimentally obtained peak of $\alpha = 1$ was shifted toward 2 because of the limitation of the finger-touching procedure (Murata et al., 2003).

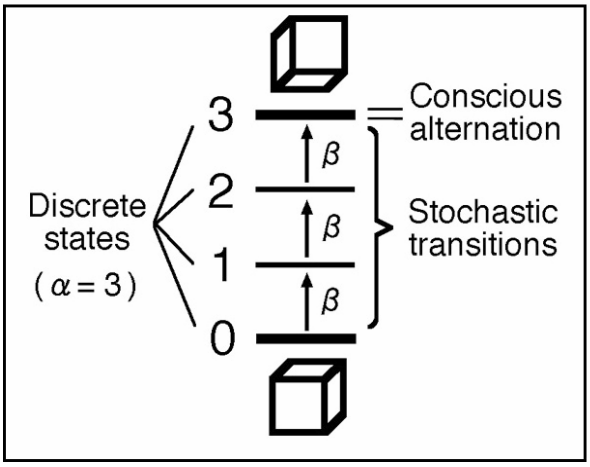

Figure 3. The discrete stochastic mechanism of perceptual alternation (e.g., $\alpha = 3$). Numbers from 0 to 3 denote discrete states of the brain. Elementary stochastic transitions between the states occur with a rate of β. Transition up to the αth state causes an alternation of conscious percept.

Experiment 2

Method

Participants. Ninety-one students (age 21.6±1.7 years) were recruited from the academic environments of Kanazawa Institute of Technology, and gave written informed consent to participate in the experiments according to the institutional guidelines approved by the Ethics Committee for Human and Animal Research of National Institute of Information and Communications Technology. Each subject had normal or corrected-to-normal vision. All the subjects participated in all of the following eight kinds of experiments with being paid.

Stimuli and Design. Seven kinds of rivalrous stimuli were used (Figure 1a-g): BR, NC, BN, RU, BO, AM (abbreviations are the same as Experiment 1) and a bistable rotating sphere (RS). For AM, the two frames were presented alternately with an SOA of 167 ms. For RS, the movie frame rate was 15 Hz and the cycle period was 40 seconds. Apparatuses and instructions are the same as Experiment 1. The seven stimuli were randomly arranged for each subject, except keeping NC-BN in this succession. After the seven rivalry experiments, to see properties specific to perceptual rivalry, we had a control experiment, in which the subjects were required to mime finger-reports in as similar timing to perceptual alternation as they could with seeing only the fixation point. In a day at most one stimulus (including the control experiment) was investigated for each subject.

Data Analysis. When we applied the same procedure of GD fitting as Experiment 1 to the data of Experiment 2, the sharpness of the α histogram peaks at natural numbers varied among the stimuli; discrete peaks were clearer for BR and AM than for the other stimuli. These differences among the stimuli probably came from the differences of clearness of conscious alternation among them. To treat this problem, we improved the analysis methods in the following three points. Firstly, we adopted an efficient cost function (instead of the chi-square statistic used in Experiment 1) for the GD fitting given by:

$$R = \sum_{i=1}^{M} \frac{\{p_E(t_i) - p_G(t_i)\}^2}{p_G(t_i)\{1 - p_G(t_i)\}} \qquad (2)$$

where t_i is the ith shortest interval value, M is the number of interval values, and $p_E(ti)$ and $p_G(ti)$ are respectively the cumulative relative frequency of the experimentally obtained intervals and the cumulative GD at ti. The denominator of each term was the intrinsic variation with $p_G(ti)$, which was used for normalization of the residual. (Actually, application of this cost function to the data of Experiment 1 did not change the conclusion.) Secondly, to eliminate outliers of intervals (extraordinarily short or long intervals) in each data set, which could impose large influences on GD fitting, we estimated how large decrease of the cost function could be obtained by trimming a certain number of the smallest and largest intervals from the GD fitting. Finally, Monte Carlo simulation of the GD fitting showed that the sharpness of a histogram at natural numbers becomes worse when a data set includes fewer intervals than 200 (data not shown). Thus, in making the α histograms we avoided to include α values obtained from data sets which had fewer intervals than 100 or 150.

Results and Discussion

Figure 4 show α histograms obtained for each of the seven stimuli and the control condition. The trimming of outliers in the GD fitting was applied when removals of a certain number of the smallest or largest intervals from the

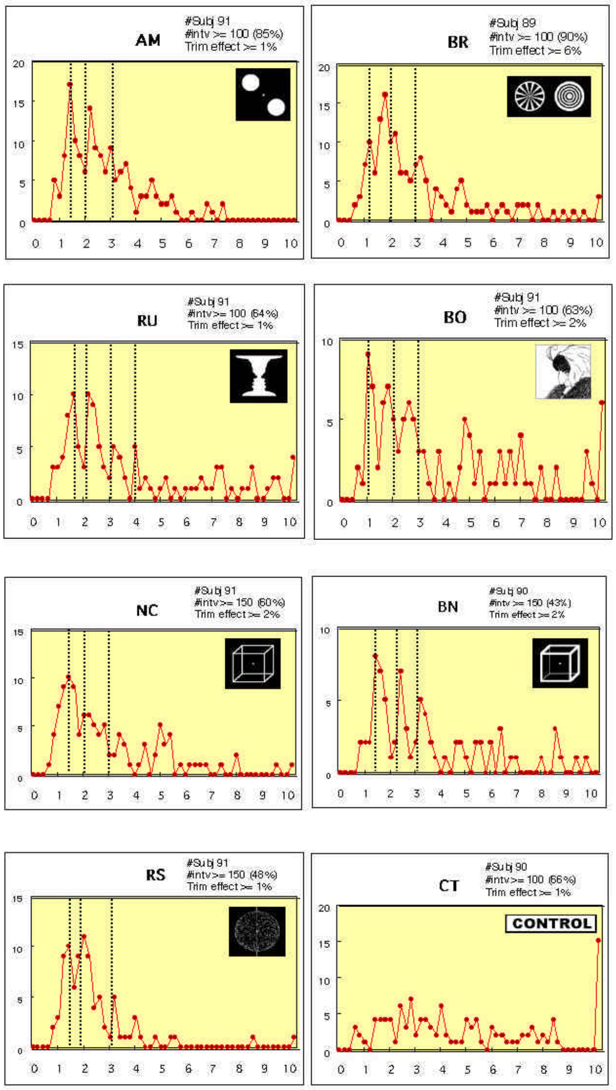

Figure 4. Histograms of α obtained from single stimuli.

GD fitting caused more than 1 or 2 % decrease of the cost function per 1% of removed intervals. Each histogram of the seven stimuli showed discrete peaks at the natural numbers of 1, 2, and 3. (The peaks of 1 can be shifted towards 2 by the effect explained above.) In some cases, peaks at 2 or 3 did not fit to the integer position but slipped by one or two bins of the histogram. We can have two possible reasons: First, the number of intervals in data sets might not be sufficient to obtain reliable integer peaks. If we exclude α values obtained from data sets of fewer intervals than 200, however, adopted αs are too few to make a histogram. Second, a certain degree of deviation from steadiness of perceptual alternation in such a prolonged observation might shift the α distribution. To discuss this issue, estimation of steadiness in perceptual alternation is necessary.

On the other hand, the result of the control condition showed the most continuous distribution of α values among the results, indicating that discreteness of α distribution could not be obtained by mimicked (or intended) fluctuations.

These results indicated that discrete stochastic process underlies each of the seven kinds of perceptual rivalry investigated here, although insufficiency of interval numbers or deviations from behavioral steadiness possibly caused small shifts of α peaks. It is unclear, however, how individual subjects contribute to the α histograms, that is, whether an individual subject take variable a values or a constant one.

Experiment 3

Method

Participants. Three subjects out of the subjects of Experiment 2 participated.

Stimuli and Design. AM and BR were used as visual stimuli under the same condition as Experiment 2. Each subject participated 10 sets of experiment for each of AM and BR (totally 20 sets). The turns of 20 sets were randomly arranged for each subject, and at most one set was done for each subject in one day.

Data Analysis. The procedures of GD fitting and outlier trimming were the same as Experiment 2. The data selection based on interval numbers, however, was not applied to avoid losses of α values because it is difficult to increase the number of data sets in such an experiment regarding individual subjects.

Results and Discussion

Figure 5 show α histograms of each subject for AM, BR and their combination. Although the number of α values obtained (40 α values in a combination histogram) were not sufficient to clarify the integer peaks, it is clear that each histogram shows a single distinct peak rather than multiple distinct peaks such as Figure 2 and Figure 4. The combined histograms suggested that an individual subject provided the same integer α value in spite of the difference of the used stimuli. Therefore, it is the most probable that the α value is intrinsic to an individual subject.

General Discussion

In the present study we quantitatively investigated statistical distributions of time intervals of perceptual alternation in various kinds of rivalry. The results showed that the distributions fit GDs well and that the shape-determining parameter of the GDs took natural numbers such as 1, 2, 3 or 4. This finding demonstrated that perceptual alternation is caused by a Poisson process. The extended version of experiments showed that this kind of discrete stochastic mechanism is common to various kinds of perceptual rivalry, and that the number of the discrete steps is probably intrinsic to an individual subject.

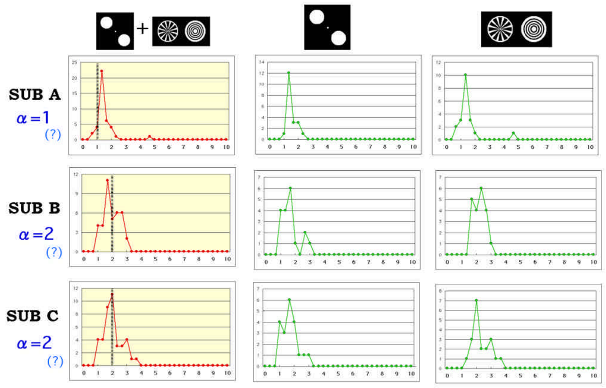

Figure 5. Histograms of α obtained from individual subjects.

All the findings of the present study are phenomenological (behavioral), and the neural mechanisms of this discrete stochastic process underlying perceptual rivalry is an open question. In the recent several years fMRI (functional magnetic resonance imaging) studies of binocular rivalry (Lumer, Friston & Rees, 1998; Tong et al., 1998; Polonsky et al. 2000) and ambiguous figure perception (Kleinschmidt et al., 1998; Sterzer et al., 2002; Tanabe et al., 2002) have shown that distributed activations of multiple cortical areas, including visual, parietal, and frontal areas, relate to perceptual alternation, suggesting that different stages of the hierarchy of visual processing are associated with perceptual rivalry (Blake & Logothetis, 2002). Although most of the neural mechanisms of perceptual rivalry have yet to be clarified, the viewpoint of "the brain a system" seems to become more important to understand perceptual rivalry because it is probable that dynamic interactions among many areas in the brain may produce quasi-stable discrete states as a system. The discrete stochastic mechanism proposed in the present study may provide a useful paradigm to investigate perceptual rivalry from such a new viewpoint.

Conclusion

Our study showed that gamma distributions, which have been known to provide good fittings to time intervals of perceptual alternation, reflect discrete stochastic process underlying perceptual rivalry. This mechanism is common to various kinds of perceptual rivalry including binocular rivalry and ambiguous figure perception. The number of discrete states in this mechanism is probably intrinsic to an individual subject. The discrete stochastic mechanism found in our study may require a new viewpoint of "the brain as a system" to understand perceptual rivalry.

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