When perceptual time stands still: Long stable memory in binocular rivalry

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We have carried out binocular rivalry experiments with a large number of subjects to obtain high-quality statistics on probability distribution of dominance duration (PDDD) for two cases where (a) the rival stimulus is continuously presented and (b) the rival stimulus is periodically removed, with stimulus-on and stimulus-off intervals $T_{on}$ and $T_{off}$ respectively. It is shown that the PDDD obtained for the latter case can be reproduced to a reasonable degree of approximation by simply using the PDDD of part (a) and slicing it at pieces of time extent $T_{on}$ and by introducing intervals of length $T_{off}$ between the on-intervals where the PDDD is set to zero. This suggests that the variables representing the perceptual state do not change significantly during long blank intervals. We argue that these findings impose challenges to theoretical models which aim at describing visual perception.

I. INTRODUCTION

Binocular rivalry (Leopold and Logothetis, 1999) is the spontaneous alternation between two perceptual states which occurs upon presentation of an ambiguous stimulus. A form of bistable perception is binocular rivalry (BR) (Blake and Logothetis, 2002) where each retina is presented with a different image dichoptically; the observer experiences perceptual rivalry between the two different percepts which correspond to the images presented to the two retinas. This phenomenon can be useful in neuroscience for many different reasons; for example, it permits dissociation of neural activity which corresponds to conscious perception from that which is related to sensory stimulation and, thus, it has been used as a tool to investigate the neural correlates of consciousness (Crick and Koch, 1995; Sterzer et al., 2009; Sterzer and Rees, 2008; Sterzer et al., 2002; Tong et al., 2006).

Nearly half a century ago, it was discovered (Orbach et al., 1966) that intermittent presentation of a bistable pattern, which appears and disappears every few seconds, decreases the frequency of perceptual changes in bistable perception. In a more recent remarkable study (Leopold et al., 2002), it was demonstrated that a periodic removal of the stimulus, which causes bistable perception, can lead to nearly freezing the same perception of the rival stimulus. Following these measurements, Chen and He (Chen and He, 2004), in the case of binocular rivalry, allowed for swapping of the two rival stimuli between the two eyes during intermittent presentations. They found that the stabilization occurs only when the same stimulus was presented to the same retinal location. Furthermore, Chen and He (Chen and He, 2004) and Pearson and Clifford (Pearson and Clifford, 2004) have studied the consequence of swapping other characteristics of the stimuli, such as color and orientation. These results have been interpreted that the neural processing of the bistable stimuli involves a form of memory storage across the blank interval (O’Shea, 2004; Pearson and Brascamp, 2008).

While for the case of binocular rivalry with continuous stimulus there are available results for the so-called probability distribution of dominance duration (PDDD) (Lehky, 1995; Levelt, 1968), so far, there are no studies of the PDDD for the case of periodically interrupted stimulus. One reason for the lack of such studies may be the fact that, in order to obtain reasonably good statistics of the PDDD in the case of interrupted stimulus, compared to the continuous stimulus case, a much larger total subject test-time is required. In this paper we have carried out binocular rivalry experiments using a large number of subjects for high-quality statistics to obtain the probability distribution of dominance duration (PDDD) for two cases where (a) the stimulus is continuous and (b) the stimulus is periodically removed. The definition of the PDDD for case (a) is well-known. We define the PDDD for case (b) as the probability density for a perceptual change to occur at time $t$, measured from the time of the previous percept change, under the condition that the stimulus on-off periodic cycle starts at precisely the time of the previous recorded event of percept change.

We find that the PDDD for the case where the stimulus is periodically removed with stimulus-on and stimulus-off intervals $T_{on}$ and $T_{off}$ respectively, can be constructed from the PDDD which is obtained for continuously presented stimulus by simply slicing the distribution to pieces of time extent $T_{on}$ and introducing intervals of time extent $T_{off}$ between these slices where the PDDD is set to zero. Inversely, starting from the PDDD obtained with the periodically removed stimulus and simply erasing the blank intervals and “sewing” together the stimulus-on pieces of the distribution, the PDDD for continuous stimulus can be approximately constructed. This suggests that there is approximately no significant change of the state of the perceived stimulus during the blank intervals.

The paper is organized as follows. In Sec. II we discuss what precisely we measured and we present the technical details of the method used. In Sec. III we discuss the experimental results for the cases of continuous and periodically interrupted stimulus. In Sec. IIIA we analyze...
II. EXPERIMENTAL METHOD

A. Subjects

A large number of subjects (53 total) participated in the experiments reported in the present work and they were all undergraduate students at Florida State University (FSU). The project received prior approval by the FSU Human Subjects Committee and the students who agreed to participate in this study signed an appropriate consent form. In order to achieve good statistical quality of the probability distribution, especially for the case of periodically removed stimulus, such a large number of subjects was necessary.

B. Apparatus and Stimuli

A stimulus similar to the image shown as in Fig. 1 (top) was projected on a Viewsonic Optiquest Q71 17” CRT display (at 1024 × 768 resolution and 60-Hz refresh rate) with 0.23 mm dot pitch which was connected to a computer; the display was controlled through a written and compiled Labview application running under the Windows operating system. This application a) takes input from the mouse interrupt when the mouse button was pressed by the subject, b) records the time of such an event, and c) resets the timer which controls the periodically presented stimulus to zero when the subject presses the mouse button (see discussion below). Each subject was viewing the stimulus by wearing a pair of glasses which had a red and a blue filter for the left and right eye respectively. The colors of the image, as viewed on the above described display, were carefully chosen such that, through the red/blue filters used, the left or right retina would see clear horizontal or vertical stripes similar to those shown on the left or the right bottom of Fig 1. The images shown at the bottom of Fig. 1 when viewed in color (in the on-line version not the printed version of the paper), are similar to what an observer sees through the filters by closing the other eye. The actual size of the stimulus was 4.5 cm × 4.5 cm and was set at a distance of 100 cm from the subject’s eyes (2.6° × 2.6° and 0.32° distance between two successive horizontal or vertical stripes). With the choice of contrast level made for the two sets of stripes, we found that the average dominance duration for either eye was approximately the same (Levelt, 1968).

The stimulus was periodically presented for a time interval $T_{on}$ and removed for a time interval $T_{off}$, as long as there was no indication that the subject perceived a change. Fig. 2 (top) schematically presents the “on” (shaded area) and “off” (blank) periods in which the stimulus is presented in a periodic fashion. The subjects were instructed to press a computer mouse button when they perceive a change in the percept, i.e., from horizontal to vertical stripes or vice versa. When the subject presses the button an event is registered and at the same time, the clock that measures the length of the presentation of the stimulus is reset at the beginning of the periodic cycle. This is shown in Fig. 2 (bottom) where, at the indicated instant $t$ in time, the observer has caused a recording of an event; then the stimulus stays on for an interval $T_{on}$ starting from the moment $t$ and, if no other event registers in the mean time, the stimulus goes off for an interval $T_{off}$ and so on until the interrupt connected to the mouse registers a new event. This was achieved using Labview programming in which the interrupt connected to the mouse is coupled to the loop which causes the periodic “on-off” cycle. When the interrupt picks up the signal from the mouse input, it resets the loop which produces the periodic cycle. At the end of the procedure a file containing the time series of the events $t_0, t_1, t_2, ..., t_n, t_{n+1}, ...$, for any given subject is stored on a specified directory labeled by the observer’s assigned identification number.
The gray-shaded areas labeled as T_on denote the periods where the stimulus is presented to the subject and the blank areas labeled as T_off denote the time intervals where the stimulus is removed. At an instant of time t, indicated by the arrow, the subject responds to a perceptual change by pressing the button. Then the sequence of on-off periods is substituted by a new sequence shown in the second row where the beginning of the periodic process starts at time t. The resulting pattern of stimulus on-off periods is shown in the bottom part of the above figure.

C. Procedure

Before the actual experiment, each observer was asked to wear the glasses and was presented with the image of Fig. 1 (top) to make sure that he can experience rivalry. Then, another quick test was carried out where the observer was presented with the same stimulus but, this time, it was periodically removed and the observer was also asked to press the button when he perceived a change from the image with the stripes being horizontal (blue) to an image with vertical stripes (red) and vice versa. The subject was told to pay attention, when the image disappears and comes back, whether or not the percept comes back different and if so to press the button if not to wait until it changes. Then the subject was informed that with his/her permission three actual experiments would be carried out next: in one, the stimulus would be continuous, in the second and third, the stimulus would be periodically removed. The subjects were also informed that the duration of each of these three experiments would be approximately 10 minutes. Because some subjects either had limited time available to devote to the experiments or because they experienced some degree of fatigue at the end of the first experiment (continuous stimulus) or the second experiment they were not asked to participate in all three cases planned. As a result in the case of continuous stimulus, which was carried out first, all 53 observers participated in the experiments. In the other two cases with the periodically removed stimulus, only 42 observers participated in one case (with T_on = 1.1 sec and T_off = 3.1 sec) and only 40 observers participated in the other case (with T_on = 2.2 sec and T_off = 3.1 sec).

In producing the histograms, the time series of the events t_0, t_1, t_2, ..., t_n, t_{n+1}, ..., for any given subject, is converted to a series δt_1 = t_1 - t_0, δt_2 = t_2 - t_1, ..., δt_n = t_{n+1} - t_n, ... of elapsed times between events and the histogram of these intervals is shown in Fig. 3.

The case of continues stimulus is obtained when T_on is set to be longer than the time that the entire experiment lasts.

III. RESULTS

A. Continuous stimulus

The stimulus shown in Fig. 1 was continuously presented to 53 subjects through the two different filters for each eye as discussed above for approximately 10 minutes per subject. A total number of 16435 responses (events) were recorded. In Fig. 3 we present the histogram of the event frequencies. The calculated average value of dominance duration is 2 sec.

B. Periodic removal of stimulus

Here, we will present the results of our experiments where the stimulus was periodically removed as discussed in Sec. II. The intervals δt_i of elapsed time between successive responses are the dominance durations of either percept given the constraint that, starting from the onset of a perceptual change, the stimulus is kept on for a time T_on and, then, the stimulus is turned off for an amount of time T_off, etc., until the next perceptual change occurs at which point in time, the clock is reset to zero and the onset of a new periodic cycle starts. Data were collected for 40 observers for the case where T_on = 2.2 sec and T_off = 3.1 sec, and the histogram of the δt_i is shown in Fig. 4 (Top). In Fig. 4 (Bottom) the results are
Figure 4 (Top) The measured probability distribution of dominance duration (PDDD) averaged over 42 subjects for $T_{\text{on}} = 2.2$ sec and $T_{\text{off}} = 3.1$ sec. (Bottom) The measured PDDD averaged over 40 subjects for the case of $T_{\text{on}} = 1.1$ sec and $T_{\text{off}} = 3.1$ sec.

Figure 6 The measured PDDD for the case of $T_{\text{on}} = 2.2$ sec, $T_{\text{off}} = 3.1$ sec (Top) and for the case of $T_{\text{on}} = 1.1$ sec, $T_{\text{off}} = 3.1$ sec (Bottom) is compared to the distribution shown as an inverted curve (part b), which is obtained by slicing the $C(t)$, i.e., the one for continuous stimulus.

Figure 5 Illustration of how to obtain the probability distribution of dominance duration (PDDD) for the case where the stimulus is periodically interrupted from the PDDD obtained for the case of continuous stimulus presentation. The PDDD for continuous stimulus is sliced at segments of duration $T_{\text{on}}$ and, then, they are separated by blank intervals of duration $T_{\text{off}}$. Thus, we obtain the PDDD for interrupted stimulus shown in Fig. 6.

IV. ANALYSIS OF THE RESULTS

As illustrated in Fig. 5 the experimental PDDD obtained for continuous stimulus (after proper normalization to the same number of events) is sliced in parts of width equal to $T_{\text{on}}$ and, then, these parts are separated by intervals of time extent $T_{\text{off}}$ as shown in the inverted curves of Fig. 6. Namely, a discontinuous PDDD $D(t)$, to be compared with the case of periodically interrupted stimulus, is constructed using the PDDD $C(t)$ for the case of continuous stimulus presentation, as follows:

$$D(t) = \begin{cases} C(t - nT_{\text{off}}), & nT < t < nT + T_{\text{on}} \\ 0 & \text{otherwise} \end{cases}$$

(1)

where $n = \left\lfloor \frac{t}{T} \right\rfloor$ (the brackets stand for the integer part) and $T = T_{\text{on}} + T_{\text{off}}$, the period of the on and off process.

Notice in Fig. 6 that several of the main features of the PDDD for the case of interrupted stimulus are reasonably well reproduced using the PDDD for continuous
stimulus by this procedure. For example, the number of on-intervals where there is a significant probability as well as the distribution of the probability in each of the on-intervals is similar. Furthermore, when the value of \( T_{\text{on}} \) is smaller the number of on-interval with significant probability increase.

Some of the differences between the sliced-up continuous distribution (Eq. 1) and the experimental PDDD for the intermittent stimulus can be reconciled as follows. As it may be noticed, there are gaps of events in the off intervals, however, there are also events which fall in the gaps. The main reasons for this are

(a) the observer’s finite response time and
(b) when the stimulus reappears, the observer delays to give his/her response mainly because it takes time to make a decision on whether or not the percept is the same with the one perceived at the end of the previous stimulus presentation.

In order to make sure that this is not due to an equipment delay caused by some unknown factor, we use a photo-diode to measure the physical values of \( T_{\text{on}} \) and \( T_{\text{off}} \). Namely, a photo-diode connected to an oscilloscope is placed in front of the computer monitor and, thus, the oscilloscope registers different voltage values depending on whether on the computer monitor the image/stimulus is on or off. Using the same experimental equipment, i.e., computer, monitor and software, we presented the same stimulus with the same two conditions of on and off times presented to the observers. We found that both \( T_{\text{on}} \) and \( T_{\text{off}} \) were very close (within less than 10 milliseconds) to the input values used in this study. Then, we carried out a different experiment to measure the time delay \( \delta t \) in human response from the actual time the stimulus goes off to the time recorded. For this experiment the same stimulus was periodically presented and removed to observers (this time without wearing glasses) and we asked them to respond when they saw the stimulus disappearing. In Fig. 7 we present the distribution of the time-delay measured from the actual time where the stimulus is removed. Notice that the responses peak at \( \delta t_{\text{max}} = 0.34 \text{ secs} \). The solid line is a Lorentzian fit, i.e., to the form \( C/((t-t_0)^2 + \epsilon^2) \) which gives \( t_0 = 0.335 \text{ secs} \) and \( \epsilon = 0.0303 \text{ secs} \).

Guided by this observation we re-analyzed the PDDD data for the two cases studied here in a different way with the intention to take into consideration this delay in human reaction time. In Fig. 8 we present the distribution of the time-delay measured from the actual time where the stimulus is removed. Notice that the responses peak at \( \delta t_{\text{max}} = 0.34 \text{ secs} \). The solid line is a Lorentzian fit, i.e., to the form \( C/((t-t_0)^2 + \epsilon^2) \) which gives \( t_0 = 0.335 \text{ secs} \) and \( \epsilon = 0.0303 \text{ secs} \).

In Fig. 9 the measured PDDD for the two cases studied here is compared with the PDDD obtained as discussed in the previous paragraph (for Fig. 8) and, in addition, the
The measured PDDD for the case of $T_{on} = 2.2$ sec, $T_{off} = 3.1$ sec (Top) and for the case $T_{on} = 2.2$ sec, $T_{off} = 3.1$ sec (Bottom) is compared to the distribution shown as an inverted curve (part b), which is obtained by slicing the $C(t)$, i.e., the one for continuous stimulus where a 0.3 sec is added due to time-delay caused by finite human reaction time and, in addition, by using a Lorentzian broadening of the responses with the independently measured width of $\epsilon = 0.03$ secs.

Notice, however, that the distribution obtained by just slicing $C(t)$ has a peak very close to the on-set of the new periodic cycle while the experimental peak is delayed. This behavior is very similar in all of the on-intervals. We believe that this is due to the fact (b) discussed above namely, that when the interrupted stimulus reappears, the observer, in addition, to the standard response time, he needs time to make a conscious decision on whether the percept is the same or different with the one he was experiencing when the stimulus went off.

V. DISCUSSION AND CONCLUSIONS

The PDDD for the case where the stimulus is periodically removed has been measured for the first time. A large number of subjects were used in order to obtain reasonably good statistics.

Our analysis of our results demonstrates that, to a reasonable approximation, the main features of the PDDD with interrupted stimulus can be obtained from the PDDD which corresponds to the continuous stimulus by simply slicing the latter and introducing no response between the sliced intervals. Inversely, if we put-together the pieces of the PDDD corresponding to the case of interrupted stimulus we obtain the PDDD corresponding to the case of continuous stimulus presentation.

The results of the experiments reported in the present work, imply that there is no significant change and no significant decay of the memory of the perceived state during the stimulus interruptions. While physical time is the parameter that follows the physical change (evolution), we can define “perceptual time” as the parameter which characterizes perceptual change. This latter time, to a large extent, halts during the intervals of the stimulus interruption.

Adaptation-inhibition models cannot explain the perceptual stabilization upon stimulus interruption. In order to describe perceptual stabilization of interrupted ambiguous stimuli, Noest et al. (Noest et al., 2007) have introduced a model in which percept-choice at stimulus onset differs fundamentally from percept-switching due to inclusion of interaction between “shunting” adaptation and a near-threshold neural baseline. In order to describe the stabilization of the perceptual state in binocular rivalry Wilson (Wilson, 2007) has introduced a model in which he assumes a rapid synaptic potentiation followed by a significantly slower depression back to the original level. However, it is not at all obvious that the above models can reproduce this measured behavior of the PDDD. In both theoretical models, the dynamical variables which represent the perceived state evolve during the blank intervals; however, the present experimental results suggest that the perceptual state is approximately unaffected by time during stimulus interruptions (which last for several seconds) as shown in the present experiment. This experiment was motivated by a theoretical work of the present author (Manousakis, 2009). The experimental results of the present paper are in reasonable agreement with the prediction of that theory, i.e., Eq. [1]. It may still be premature to accept the rather radical theoretical point of view of our previous theoretical work (Manousakis, 2009) without further investigation; however, the experimental results of the present study are significant because they should serve as a benchmark by which to test any theory of bistable perception.

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