Intermittent stimulation of binocular disparate colors and central color fusion*

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Two experiments were conducted to determine the relationships between the various parameters of intermittent stimulation and the occurrence of binocular color fusion. Numerous combinations of on and off durations were presented, some synchronously and some asynchronously. Three Os were asked to report all colors experienced during the 15-sec viewing period. Experiment 1 showed that fusion can be reliably obtained with on durations of less than 100 msec in combination with off durations of more than 100 msec. Experiment 2 indicated that the limit of dichoptic onset asynchrony within which color fusion reliably occurs is 25 msec. Two possible alternative hypotheses consistent with the data are discussed.

Historically, the problem of binocular color fusion has been centered around the controversy between the Young-Helmholtz and the Hering theories of color vision. The problem has been mainly whether or not central fusion exists and the implications of such fusion or lack thereof for the two theories. As the empirical issue stands now, the occurrence of binocular fusion of different colors is considered firmly established (e.g., Hecht, 1928; Pickford, 1947; Prentice, 1948; Thomas, Dimmick, & Luria, 1961). However, as Osgood (1953) has pointed out, the puzzling fact that emerges from these studies is the difficulty of obtaining reliable color fusion, especially with the bipolar colors. For example, in the recent study of Thomas et al, when various hues were presented for 2 and 6 sec, the percentages of presentations in which fusion occurred were 3.4 and 31.0, respectively.

One exception to the general difficulty of obtaining reliable color fusion is the stimulus condition employed by Gunter (1951). Using a modified Hecht box and an episcope, he found that if red and green stimuli were presented intermittently, reliable fusion could be obtained at certain rates of repetition. Gunter's study further showed that the stimuli need not be presented simultaneously to both eyes. Color fusion was also obtained when the stimuli were presented alternately to each eye. Perry, Childers, and Dawson (1969) have subsequently confirmed Gunter's basic finding that dichoptically presented red and green are fused into yellow under intermittent vision.

The aim of the present study was to explore further the effects of intermittent binocular stimulus presentation on central

color fusion. The first experiment was concerned with the effects of a wide range of on and off durations and rates of repetition, while the second experiment was concerned with the effective limits of dichoptic stimulus onset asynchrony.

EXPERIMENT 1

Although Gunter's (1951) findings indicate that a certain intermittency of binocular stimulation of different colors gives rise to reliable central color fusion, the question concerning what characteristics of the intermittency are critical in producing fusion remains unanswered. Hence, Experiment 1 was designed to investigate the effect of different parameters of intermittency, viz, on duration, off duration, rate of repetition (cycles per second), and pulse-to-cycle fraction, on the production of a central yellow, given the independent binocular input of red and green stimuli. Various combinations of the on-off durations were presented at three different luminance levels, and the O was asked to report what color he experienced and whether the color experience remained the same during the exposure period.

Method

Apparatus. The apparatus was a

Fig. 1. Schematic drawing of one of the optical systems.

stereoscope comprising two identical, but independent, optical systems, which allowed the intermittent presentation of homogeneously illuminated circular fields of colored light. In each system the circular field was produced by using a plate of translucent rear-projection glass masked by an aluminum plate, painted flat black, with an aperture 0.8 cm in diam. Figure 1 illustrates one of the systems. The aperture was optically situated 23 cm from the O's eye and subtended a visual angle of 2 deg. Each field was illuminated by a Sylvania glow-modulator tube, controlled and powered by an Iconix system. A pair of lenses was used to produce a focused spot of light on the rear-projection glass; the spot of light was slightly larger than the aperture. The intensity and color of the fields were manipulated through the insertion of Wratten neutral-density and color filters in the focused portion of the beam. The glow-modulator tubes were initially calibrated so that the luminance of the field was 150 fL, as measured by the Spectra spot meter. Two lower luminance levels were produced by the insertion of neutral-density filters 0.5 and 1.0 in value. The two colors used, red and green, were produced by Wratten filters, Nos. 29 and 61, respectively.

The two optical systems had a common axis which was parallel to the O's frontal plane. A series of baffles was used to eliminate stray internal illumination. The apparatus was covered with black velvet cloth to eliminate stray external light. The O viewed the stimuli through right-angle prisms. When the stimuli were properly fused, the O saw a single circular field against a dark background.

Inserted in each system, behind the rear-projection glass plates but not in direct line with the glow-modulator tubes, were two 6-V miniature bulbs which illuminated the rear-projection glass. The intensity of the bulbs was attenuated with neutral-density filters to produce a dim gray circular fixation field when the glow-modulator tubes were turned off; the luminances of the fixation fields were

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0.1 fL each. These fixation fields allowed the O to maintain adequate spatial fusion during the course of the experiment. A chinrest was used to keep the position of the O's head stable.

Stimulus conditions and experimental design. The various combinations of on-off durations presented formed a matrix of nine on durations, 25, 50, 75, 100, 150, 200, 250, 300, and 350 msec, and 13 off durations, 25, 50, 75, 100, 150, 200, 250, 300, 350, 400, 450, 500, and 550 msec. An O was shown every cell in the matrix in a single experimental session. Completion of the matrix was accomplished by going either horizontally or vertically across the matrix during the sessions. For example, in a session in which the horizontal presentation was required, the E selected one of the on durations and then, starting from one of the extremes, presented all of the off durations successively. When this row was finished, another row was chosen. The selection of a row or column and the selection of either extreme as the starting point were determined randomly. The horizontal and vertical presentations were employed twice—varying the right-left location of the color filters—at each of the three luminance levels.

The resulting 12 conditions each contained the 117 cells of a matrix. Each cell was presented for 15 sec. Holding viewing time constant in such a manner meant that the number of flashes varied with both the on and off durations. That is, longer on and/or off durations resulted in a smaller number of flashes being presented in the 15-sec viewing period. However, preliminary investigations indicated that extending the viewing period to as long as 30 sec did not change the nature of the report by the Os. The interval between successive presentations of the stimuli, i.e., each cell, was 15-20 sec.

Procedure

The O was situated in a light-tight room, while the E was in an adjacent room with the timing system. Before each experimental session, the O made two adjustments of the apparatus. First, he adjusted the prisms so that a single clear circular field was binocularly observed. Second, in order to control for ocular dominance, he adjusted the brightness of one of the circular fields by inserting additional neutral-density filters until the colors appeared to rival with equal durations. While the total value of the filters added differed among the Os and also from day to day, additions were on the side of the green filter. In no case did any O attenuate the brightness of the dominant side by more than 0.3 log units.

After these adjustments, the O dark adapted for 10 min before an experimental session began. Midway through an experimental session, the O rested for 10 min, again in total darkness.

The primary task for the O was to report the color(s) observed during the 15-sec viewing period. A color-naming method similar to that of Boynton, Schafer, and Nuen (1966) was used to report the color(s) observed. There were three primary responses: red, green, and yellow. The intervening hues between red and yellow or between green and yellow were reported, using a combination of red and yellow or green and yellow, respectively. The predominant color was always reported first. When, for example, "yellow-green" was reported, it meant that all the flashes appeared to be the same color and that the color experience was primarily yellow but also included some component of green. When unitary hue from flash to flash was not experienced, typical responses included "red-yellow and green-yellow" or "red and red-yellow and green-yellow."

The three authors of this study served as Os. The Os were highly experienced in the experimental situation in that they had participated in extensive preliminary studies. Each person alternated in the roles of E and O. For a given O, there was only one experimental session a day; the experiment was completed in a span of 2 months.

Results and Discussion

During the experiment all three Os felt a lack of confidence concerning the reliability of the color name assigned to observations made at different stages of the experiment, e.g., reports of "yellow" at an early stage of a session might not have been given to the same quality at a later stage. Therefore, in the classification of responses, reports of "yellow," "yellow-green," or "yellow-red" were classified as fusion and reports of "red," "green," "green-yellow," or "red-yellow" were classified as dominance. With these classifications, two different levels of analyses were performed. One level of analysis was concerned with whether or not fusion had occurred in a given viewing period, and another was concerned with whether or not the fusion was a stable one. In the former analysis an observation was an instance of fusion if the O reported at least one fusion, as defined above, during any portion of the viewing period. In the latter analysis an observation was an instance of stable fusion if the O reported only "yellow," only "yellow-green," or only "yellow-red" during the 15-sec viewing period. (The second tabulation is a subset of the first.) An examination of the

Fig. 2. Percent of viewing periods in which fusion or stable fusion occurred as a function of on duration for the three luminance levels.

data indicated that the distribution of responses was similar for different Os, and for the two types of presentations and the right-left position of the color filters. Hence, the data within each luminance level were combined and tabulated in terms of the 9 by 13 matrix. The analysis examined the percent of viewing periods in which fusion, or stable fusion, was reported for a particular cell.

An analysis of the data shows that the stimulus conditions in which fusion and a stable fusion of colors occur can be specified in terms of on and off durations alone. Figure 2 presents the percents of fusion and stable fusion as a function of on duration, and Fig. 3 presents the percents as a function of off durations. The percents of viewing periods in which fusion occurred are consistently higher than that of the percents of viewing periods in which stable fusion occurred. Figure 1 indicates that the percents of both fusion and stable fusion tend to increase initially but decrease monotonically after 100 msec. Figure 3 indicates that the percents of both fusion and stable fusion increase up to an off duration of 100 msec, and that after 100 msec the percents are relatively constant. Therefore, the optimal on-off duration to obtain central color mixing are: the on durations shorter than 100 msec and the off durations longer than 100 msec. The data also indicate that there was no clustering of stable fusion at any rate of repetition or pulse-to-cycle fraction. That is, as long as the on durations of the presentation were 100 msec or less, stable

Fig. 3. Percent of viewing periods in which fusion or stable fusion occurred as a function of off duration for the three luminance levels.

fusion tended to occur at rates of repetition as high as 10 cycles per second and as low as 1.5 cycles per second. Conversely, if the on duration was more than 100 msec, stable fusion tended not to occur, even though the rate of repetition was between 10 and 1.5 cycles per second. Similarly, for a given pulse-to-cycle fraction, stable fusion occurred if the on duration was 100 msec or less and tended not to occur if the on duration was greater than 100 msec. The same type of response distribution is shown when the occurrence of fusion is considered. Therefore, for both stable fusion and fusion, there does not appear to be a critical or optimum rate of repetition or pulse-to-cycle fraction in which they occur. In Gunter's experimental situation (1951), a constant aperture was employed on a sector disk to produce intermittency of stimulation. Hence, the pulse-to-cycle fraction was kept constant, and the analysis was done in terms of rate of repetition. However, the data of the present experiment indicate that the rate of repetition per se is not the critical variable.

The fact that repetition is not important is also suggested by some supplementary data. Two Os were given single flashes of various durations at the highest luminance level used in the experiment. Both Os consistently reported seeing yellow when the flash duration was 100 msec or less. The implication that the occurrence of fusion is not related to rate of repetition but primarily to on durations makes the interpretation of the study by Crovitz and Lipscomb (1963) and Crovitz (1964) difficult. They were unable to obtain

fusion when red and green Munsell colors were dichoptically presented in single 100-msec exposures. Rather, they found that the temporal visual fields of each eye dominated when the targets were large (10 deg x 13 deg) but the nasal visual fields of each eye dominated when the targets were small (2 deg 12 min x 2 deg 12 min). The occurrence of bipartite fields was never experienced in the present experiment.

The brighter stimulus produced larger percents of both the fusion and stable fusion, but the optimum on and off durations remained approximately the same for all three luminance levels. This relationship between brightness and the occurrence of fusion can also be seen in the tendency for the percents of stable fusion to be lower for very short on durations. That is, with on duration of 25 msec, the operation of Bloch's law reduced the brightness of the stimuli, which then produced a lower percent of stable fusion.

The relative independence of luminance level on the optimal on and off durations is not entirely consistent with Gunter's finding that higher intensity of stimuli required higher rate of repetition. The higher rate would entail shorter on and off durations with his procedure, but there is no such requirement suggested from the present data. This apparent difference is probably due to the different procedures employed. Possibly the aperture in the sector disk employed by Gunter was such as to create a range of on durations in which Bloch's law on apparent brightness was operating. Because his Os were varying the rate of presentation to obtain the "best" fused product, e.g., yellow, possibly the low-intensity stimuli could produce fusion (as defined in the present experiment), but with shorter on duration the central color obtained may have been too dark to fit the best fusion criterion. Conversely, for the higher intensity stimuli, shorter on duration might have produced too bright a fused color to fit the best fused criterion.

EXPERIMENT 2

The primary consideration in Experiment 1 was the investigation of the parameters of different intermittency when the pulses of light were presented synchronously to both eyes. However, Gunter (1951) has shown that simultaneous presentation of two pulses is not necessary for central fusion of colors. Hence, Experiment 2 was conducted to assess the effects of varying dichoptic stimulus onset asynchrony (SOA) on the production of central yellow, given the green input to one eye and the red input to the other eye. The onset asynchrony was varied for three different on durations, and

the Os were again asked to report the colors experienced and whether or not a unitary hue was experienced for a given viewing period.

Method

Apparatus. The apparatus used was identical to that used in Experiment 1. However, due to nonexperimental factors, the experiment could no longer be conducted in adjacent rooms. The use of approximately 75 m of extension cable to the glow modulators resulted in a voltage drop and, consequently, a drop in the maximum glow-modulator intensity from 150 to 50 fL. Hence, the experiment was run at the latter intensity prior to the insertion of color filters.

Procedure. Based on the results of Experiment 1, the on durations of 25, 50, and 100 msec were used. Since the results also indicated that off durations were not critical beyond 100 msec, a fixed off duration of 250 msec was used for each on duration. The SOA values used (0, 12.5, 25, 50, 75, 100, and 125) for each of the three on durations produced a 3 by 7 matrix.

For each O four observations were recorded for each of the 3 by 7 cells in the matrix to control for possible left-right eye differences. These observations were made under the following conditions: the left eye receiving the green input first, the green input second, the red input first, and the red input second. Two matrices were completed in a single session for each O. Since the matrix was small, the cells were presented randomly. (In Experiment 1 only the selection of rows and columns was randomized.) Because more complex adjustment of the timing apparatus was necessary, the intertrial interval was extended to 30-40 sec. The same three Os in Experiment 1 again served in Experiment 2.

Results and Discussion

The analysis to be reported here is concerned with what SOA would produce fusion for each of the three on durations. As with the data analysis for Experiment 1, each color name reported was classified as fusion or dominance, and an analysis was performed for both fusion and stable fusion. The data obtained for the three Os and the right-left placement of the color filters were similar and, therefore, were combined for the analyses. Figure 4 summarizes the occurrence of fusion and the occurrence of stable fusion as a function of SOA for the three on durations. The figure indicates that there is a monotonic decrease of the percent of fusion and stable fusion as the SOA increases for all three on durations. Also, as

Fig. 4. Percent of viewing periods in which fusion or stable fusion occurred as a function of dichoptic stimulus onset asynchrony for the three on durations.

in the results of Experiment 1, the percent of fusion was consistently higher than the percent of stable fusion for all three on durations. As Fig. 4 illustrates, all three on durations produced a similar result. The percent of fusion reported for the three on durations was approximately equal for all SOA values, and there is a gradual decline in the percent, until it approaches 0% at the SOA of 125 msec. Examinations of the results related to stable fusion indicate that the on duration of 100 msec produced a smaller percent than did the other two on durations. This result was primarily because one O experienced no stable fusion for this particular on duration for all SOA values. Although the percents of stable fusions are different for different on durations, the start of the decline of reliable fusion as a function of SOA is about the same for all three on durations. At the SOA of 50 msec, there is very little stable fusion reported, and at 75 msec, there is no stable fusion for all three on durations.

The results indicate that temporal overlap of two stimulus inputs per se is not a necessary condition for central fusion. For 25-msec on duration, fusion occurs beyond the SOA of 25 msec, but for the on duration of 100 msec, the percent of fusion is very near zero, even when there is some temporal overlap. Whatever mechanism is involved in producing central fusion, the limit of asynchrony that can be tolerated for the different on durations seems to be around 25 msec. The results confirm Gunter's (1951) finding that simultaneous presentation is not necessary to obtain central fusion. But, from Gunter's reports of his procedures, it is

impossible to determine what SOA or on duration was involved in his study. Hence, a direct comparison with the present results is impossible.

DISCUSSION

The two experiments conducted specified some of the parameters needed to obtain central fusion when stimuli are presented intermittently. The results of Experiment 1 indicated that the optimal on-off durations in which fusion occurs when the two inputs are presented simultaneously are on durations of less than 100 msec and off durations of more than 100 msec. Also, Experiment 2 revealed that the limit of asynchrony of two inputs in which fusion occurs is around 25 msec. Furthermore, repetition of stimulus input is not necessary. If a single flash of less than 100 msec is presented, fusion is consistently produced. With a single flash or repetition of flashes, one fact that emerges from the data is the reliability or ease of obtaining central color mixture, in contrast to most of the previous studies. Hence, the results of the present study place a qualification on the statement that relatively long exposure times of around 5-10 sec, or even more than 30 sec, are required for color fusion to occur (Thomas et al, 1961; Prentice, 1948).

The experiments were conducted to determine some of the parameters that are related to producing central fusion and were not based on a hypothesis suggested by a theory. However, some comments concerning theoretical questions are in order. Historically, binocular color mixing was thought to be one of the experimental situations in which one could determine the validity of the Young-Helmholtz trichromatic theory or Hering's opponent process theory. However, if one accepts the prevalent view that both types of processes occur at different levels of the visual system (cf. De Valois & Jacobs, 1968; Svaetichin, Negishi, & Fatehchand, 1964), then the occurrence or nonoccurrence of central fusion would not negate the validity of either theory. Hence, the results of the present experiments are not directly relevant to the confirmation or refutation of two theories. However, the results may be directly relevant to the question of what mechanism is involved in binocular rivalry, dominance, or fusion. The parameters determined by the present study suggest two alternative mechanisms, either of which may be operating.

One possible mechanism is suggested by the notion that the visual system transmits information to the central nervous system only when a spatial or temporal change of stimulation occurs on the retina-eye

movements being one of the primary determinants of how much information is transmitted (cf. Festinger, 1969; Heckenmueller, 1965; Yarbus, 1967). If it is assumed that binocular integration occurs when the information from each monocular input is equal either qualitatively or quantitatively, then the following suggestion can be made. Fusion occurs for stimulus presentations of short durations because eye movements are removed as a determinant of information input; consequently, the simultaneous on- and offset of the stimulus results in an equal amount of information being transmitted by each eye. For a longer stimulus input, an asymmetrical amount of information is transmitted, as there is an asymmetry in the amount of movement in each eye (cf. Yarbus, 1967). This asymmetry, as it fluctuates between eyes, produces rivalry.

Another possible mechanism that can explain the data obtained is suggested by the notion of contralateral suppression (cf. Asher, 1953; Hochberg, 1964; Kaufman, 1963; Levett, 1965). Whereas the eye-movement hypothesis accounts for rivalry by the fluctuating asymmetrical input of information, the suppression hypothesis suggests that rivalry occurs when, successively, one visual field actively suppresses the input of the contralateral field. Presumably, there is a time requirement for suppression to develop, and the short on durations at which fusion occurred may represent the time period before such suppression is developed. For a longer stimulus input, the time requirement for the development of suppression is exceeded and rivalry develops as the increase-decrease of suppression fluctuates between the two eyes. Instances of fusion occur when, in the process of fluctuating, the amount of suppression of one visual field on the other is momentarily equated.

Both of these possibilities imply that if on durations of, say, 250 msec are presented simultaneously, an O will experience fusion initially, then experience the stimulus input of one eye (e.g., first yellow is experienced, then green or red). However, this is not what was found. When most of the on durations longer than the optimal on duration were presented, what was experienced was a dominance for a given flash, i.e., experience of only one of stimulus input red or green. Therefore, whichever possibility is correct, one must postulate the operation of an additional mechanism such as retroactive interference or quantal analyzer (as opposed to continuous analyzer). The present data are consistent with both possibilities.

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