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THE LESS YOU SEE IT, THE FASTER IT MOVES: SHORTENING THE "ON-TIME" SPEEDS UP APPARENT MOTION

DEBORAH GIASCHI and STUART ANSTIS
Department of Psychology, York University, 4700 Keele Street, North York, Ontario, Canada M3J 1P3

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Abstract—The apparent motion (AM) created by two spots illuminated in alternation looks **faster** when there is dark temporal interval (ISI) between the offset of one spot and the onset of the other than when the spots are presented immediately after one another (no ISI), even though the temporal frequency and the spatial separation between spots are held constant. AM_{ISI} looks 18.6% faster than $AM_{no\ ISI}$ at temporal frequencies between 1.5 and 4.5 Hz. Reducing the duty cycle from 0.5 to 0.05 increases the apparent speedup to 30%. This difference in subjective speed is not due to differential saturation of velocity detectors, nor to the apparent spatial separation between spots, nor to differences in the time-averaged luminance of the stimuli. It is the "on-time", the time for which the spot is visible in one position, that determines the subjective speed. The longer the on-time, the slower the spot appears to move.

Apparent motion Interstimulus interval Illusion Movement Velocity

INTRODUCTION

When two stationary spots of light are illuminated at a suitable alternation rate, phase, and spatial separation, an observer sees a single spot moving back and forth. This apparent motion (AM) may be seen when the second spot is presented immediately after the first, or when there is a dark interstimulus interval (ISI) between the presentations of the spots. When the subjective speed of apparent motion produced by these two stimulus configurations is compared, an interesting phenomenon emerges. The AM when the spots are temporally separated by a dark interval (AM_{ISI}) looks faster than when there is no pause between the spots ($AM_{no\ ISI}$), even though the temporal frequency and the spatial separation between the spots are the same (see Fig. 1).

Temporal frequency is the number of cycles per second, and for apparent motion, one **cycle** includes the presentation of the first spot and the presentation of all subsequent spots along the motion path, up to but not including the next presentation of the first spot. **Stimulus onset asynchrony (SOA)** is the time between the onset of one spot and the onset of the next spot along the motion path, and it is equal to the duration of one **cycle** divided by the number of spots in a **cycle**. **SOA** may be divided into **"on-time"**, the time for which a particular spot is illuminated and **ISI** or **"off-time"**, the dark time between the offset of one spot and the onset of the next spot. The **duty cycle** is the ratio of **on-time** to **the duration of one cycle**. In Fig. 1a, the SOA and the on-time are equal, there is no ISI, and the duty cycle is 0.5. In Fig. 1b, the ISI and the on-time are equal, and the duty cycle is 0.25.

Is this difference in subjective speed an accurate reflection of physical differences between the stimuli, or is it nonveridical?

In mechanics, **speed** (*Sp*) is defined as distance travelled (*d*) per unit time (*t*): $Sp = d/t$, and **velocity** is **speed** in a particular direction. Since our AM stimuli have a changing directional component, the term **speed** will be used when referring to their change in distance with time. The distance travelled by an AM stimulus is the spatial separation (s) between spots. It is not clear how time should be defined. Many researchers have assumed that the duration of the ISI is the correct value for time (Kaufman *et al.*, 1971; Beck and Stevens, 1972), yielding the equation:

$$Sp = s/\mathrm{ISI} \tag{1}$$

However, the equation yields an infinite value for the speed of $AM_{no\ ISI}$ for which ISI equals zero. To remedy this problem, Kolers (1972) suggested the following modification to the equation:

$$Sp = s/\mathrm{SOA} \tag{2}$$

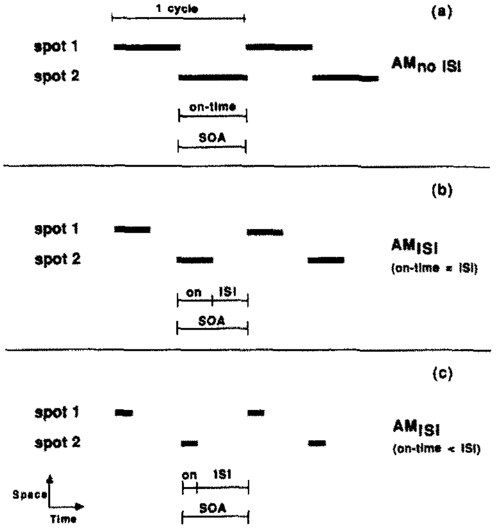

Fig. 1. Three stimulus configurations that give apparent motion. The thick lines indicate the duration of a visible spot in a certain position, its on-time. Stimulus onset asynchrony (SOA) and interstimulus interval (ISI) are also indicated. AM_{ISI}, with on-time and ISI equal, shown in (b) looks faster than $AM_{no\ ISI}$ shown in (a). If the ISI is longer than the on-time (c), the subjective speed increases further.

How does the subjective speed of AM relate to the physical speed, *Sp*? If our perception is veridical and speed is defined according to equation (1), AM should look slower not faster as the ISI increases because speed is inversely proportional to time. If our perception is veridical and speed is defined according to equation (2), AM_{ISI} and $AM_{no\ ISI}$ should appear to have the same speed, but we have found that AM_{ISI} appears to move faster. Thus, neither equation (1) nor equation (2) suggests a reason for the difference in subjective speed.

Our aim was to find out why AM_{ISI} looks faster than $AM_{no\ ISI}$. Specifically, experiments tested whether the apparent speedup was due to a difference in (a) the subjective flicker rate of each stationary spot, (b) the duration of the ISI or of the on-time of the stimuli, (c) the subjective spatial separation between spots, or (d) the time-averaged luminance of the stimuli. To anticipate, results showed that a difference in the on-time of the spots was responsible for the apparent speedup. The shorter the on-time, the faster the subjective speed.

METHODS

Observers

The observers for Expts 1 and 2 were two male and three female graduate students. All were practised in psychophysical observations, and four were naive about the purpose of the experiment. Four of these five observers participated in the remaining two experiments. Observers were paid an hourly fee for their services.

Apparatus

The stimuli were generated on a panel of green, light emitting diodes (LEDs) separated horizontally by 1 deg between centres. Each LED was 0.5 deg in diameter, with a peak wavelength of 565 nm and a luminance of 600 cd/m^2, as illustrated in Fig. 2. A central red LED, 0.1 deg in diameter, served as a fixation point. The LEDs were turned on and off by an APPLE II+ microcomputer with an Interactive Structures Digital Interface (DI09) card. Observers viewed the display binocularly under light adapted conditions from a distance of 114 cm. An adjustable chinrest was used to steady the head.

Procedure

A two-interval forced-choice procedure was used to measure the difference in the subjective speeds of the stimuli of interest in each experiment. Stimuli were presented in a random double staircase (Cornsweet, 1962) with temporal step size determined by Taylor and

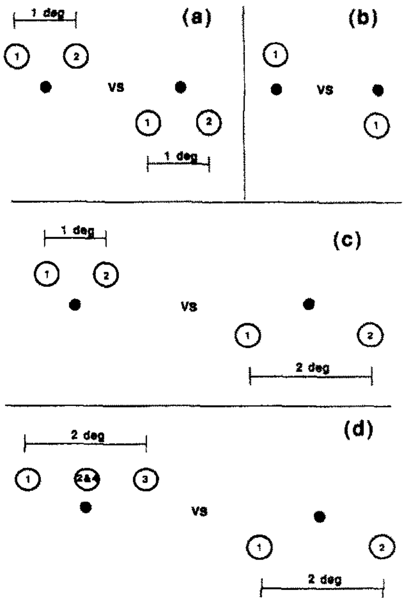

Fig. 2. The stimulus displays for (a) Expt 1, (b) Expt 2, (c) Expt 3, and (d) Expts 3 and 4. A horizontal sequence of LEDs above or below the fixation point was illuminated as shown to give the impression of a single spot of light moving back and forth. The numbers inside the spots indicate the order of presentation.

Creelman's (1967) Parameter Estimation by Sequential Testing (PEST) procedure. The procedure converged on the 50% point of the psychometric function [the point of subjective equality (PSE)]. Each trial comprised two time intervals separated by a 0.5 sec dark period, with one time interval containing a standard stimulus of fixed temporal frequency and the other a comparison stimulus of variable frequency. Each time interval contained three cycles of apparent motion (flicker in the case of Expt 2). A beep marked the beginning of each interval. The observer's task was to press one of two switches to indicate which interval contained the faster apparent motion (flicker in Expt 2). The next trial was presented 1.5 sec after a response. If the comparison stimulus was judged *faster* than the standard, its temporal frequency was decreased on the next trial and vice versa. Each time the direction of the staircase reversed, the step size was halved.

Initially, the comparison stimulus was always faster than the standard on one staircase and slower on the other. A run continued until the next step size required by the PEST routine was less than 2% of the standard temporal frequency. This was the smallest discriminable difference in speed, determined in pilot tests. *A typical run ended after 20 or 30 trials. The PSE, measured in Hz, was taken as the next level of the comparison that would have been presented in each staircase, as recommended by Taylor and Creelman (1967). Four runs, yielding eight estimates of the PSE, were collected for each comparison stimulus in every experiment.

At the start of each run, the spatial position of the standard (above or below the fixation point), and the order of presentation (standard or comparison first) were randomly determined. The comparison and standard were presented on opposite sides of the fixation point. This randomization served to reduce order and practice effects. Anstis *et al.* (1985) have shown that the perception of apparent motion degenerates into the perception of two spots flickering in phase when the stimuli are viewed for more than a few seconds. The possibility of such *adaptation* was reduced by presenting the standard and comparison stimuli to different points on the retina and by limiting the presentation of all stimuli to three cycles.

Analysis

The PSEs were converted to apparent speedup scores by the following formula:

$$\text{Speedup}\ (\%) = 100 \times \frac{(\text{PSE} - \text{temporal frequency of standard})}{\text{temporal frequency of standard}}$$

t-tests were used to test whether the apparent speedup was significantly greater than zero, and repeated measures analysis of variance was used to test for differences in apparent speedup across experimental conditions. Where appropriate, main effects were further investigated with orthogonal F comparisons (Gaito, 1973). Data for individual observers are not presented since no significant differences among observers were found.

RESULTS AND DISCUSSION

Experiment 1: the motion speedup effect

The first experiment was designed to measure the difference in the subjective speeds of AM_{ISI} and $AM_{no\ ISI}$.

Speedup as a function of temporal frequency. The temporal frequency of the AM_{ISI} standard was held constant throughout a run, while the temporal frequency of the $AM_{no\ ISI}$ comparison was varied to obtain a match in speed. On different runs, matches were made at standard frequencies of 1.5, 2.0, 3.0, 4.0, 4.5 and 5.0 Hz. These particular values were chosen to cover the range of frequencies over which apparent motion is typically reported (Caelli and Finlay, 1981; Tyler, 1973), and to narrow in on possible upper and lower frequency limits for the difference in subjective speed. The duty cycle of AM_{ISI} was 0.25 on all runs (i.e. the ISI and on-time were equal).

In all cases, AM_{ISI} looked faster than $AM_{no\ ISI}$ (all differences were significant at the 0.005 confidence level). The percentage speedup is plotted as a function of the temporal frequency of the standard in the upper regression line of Fig. 3 (solid circles). Each datum point is the mean of eight readings × five observers. Percent speedup was constant for all temporal frequencies ($F[4,16] = 0.047$, $P > 0.05$), except for

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*This is slightly better than the 3–4% discrimination reported by McKee (1981). This inconsistency may be related to task difficulty. McKee's observers were asked to judge the speed of each stimulus as faster or slower than the mean speed of seven possible speeds. Our observers had the easier task of judging the speed of each stimulus relative to a standard presented with it, thus the variability may have been smaller which would produce a lower speed-discrimination threshold.

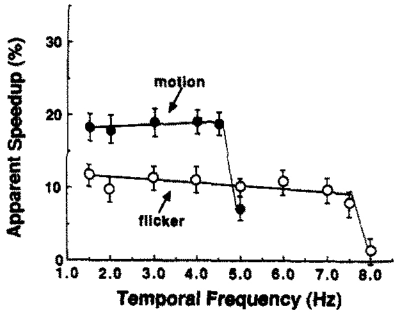

Fig. 3. Percentage apparent speedup of $\mathrm{AM}_{\mathrm{ISI}}$ as a function of temporal frequency. ● (motion): $\mathrm{AM}_{\mathrm{ISI}}$ appeared to move 18.6% faster than $\mathrm{AM}_{\mathrm{no\ ISI}}$ over a range of temporal frequencies from 1.5 to 4.5 Hz. The effect dropped off at higher frequencies where AM started to fail. ○ (flicker): when one of the spots was covered up, the single $\mathrm{AM}_{\mathrm{ISI}}$ spot appeared to flicker 10.3% faster than the single $\mathrm{AM}_{\mathrm{no\ ISI}}$ spot at frequencies between 1.5 and 7.5 Hz. The flicker effect was significantly smaller than the motion effect.

the point at 5 Hz. Thus, $\mathrm{AM}_{\mathrm{ISI}}$ was 18.6% faster than $\mathrm{AM}_{\mathrm{no\ ISI}}$ at temporal frequencies between 1.5 and 4.5 Hz. The smaller apparent speedup at 5 Hz may have been due to the poor quality of the motion percept. The frequency of 5 Hz is approaching the upper threshold of apparent motion, at which point the perception of one spot moving is replaced by the perception of two spots flickering in place. This suggests that a similar, but smaller speedup effect should exist in the subjective flicker rate of each stationary spot. This possibility was tested in Expt 2.

Speedup as a function of duty cycle. The temporal frequency of the standard ($\mathrm{AM}_{\mathrm{ISI}}$) was fixed at 3.0 Hz, but the duty cycle of this stimulus was different on different runs. The comparison ($\mathrm{AM}_{\mathrm{no\ ISI}}$) had a fixed duty cycle of 0.5 (Fig. 1a), but its temporal frequency was varied to obtain a match in speed. Matches were made with the standard at duty cycles of 0.05, 0.15, 0.25, 0.35 and 0.45.

The percentage speedup is plotted as a function of duty cycle in the upper regression line of Fig. 4 (solid circles). Percentage speedup varied significantly with duty cycle ($F[4,9] = 39.324$, $P < 0.01$), increasing as the ISI increased. It would be equally correct to say that the percentage speedup increased as the on-time decreased. There is not enough information in this experiment to show whether subjective speed was influenced by ISI or by on-time. Experiment 3 may shed some light on this question. It was not possible to measure the apparent speedup at duty cycles greater than 0.5 because the perception of motion is very weak when both spots are visible at the same time. Hypothetically such stimuli would appear to move more slowly than the standard and fall below the zero line as indicated by the dotted line in Fig. 4. As we will see in Expt 2, such a slow down was found for a single spot flickering at duty cycles greater than 0.5

Experiment 2: the flicker speedup effect

A spot that jumps back and forth in apparent motion can also be regarded as two spots flickering in counterphase. In Expt 2 we looked for a speedup in a single flickering spot by repeating Expt 1 with one of the LEDs covered up (Fig. 2b). Thus, observers chose the interval in which the spot appeared to be **flickering** faster.

Speedup as a function of temporal frequency. Percentage apparent speedup as a function of temporal frequency is shown in the lower regression line of Fig. 3 (open circles). A single $\mathrm{AM}_{\mathrm{ISI}}$ spot (duty cycle = 0.25) appeared to flicker faster than a single $\mathrm{AM}_{\mathrm{no\ ISI}}$ spot (duty cycle = 0.5) at frequencies between 1.5 and 7.5 Hz (significant at the 0.01 confidence level). The difference in subjective flicker rate was not significant at 8.0 Hz ($t[4] = 3.52$, $P > 0.05$). The single $\mathrm{AM}_{\mathrm{ISI}}$ spot appeared to flicker a constant 10.3% faster than the $\mathrm{AM}_{\mathrm{no\ ISI}}$ spot at all

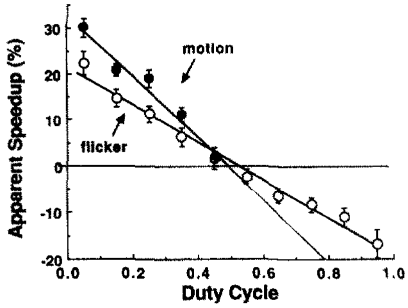

Fig. 4. Percentage apparent speedup as a function of the duty cycle of $\mathrm{AM}_{\mathrm{ISI}}$. Each point is the mean of eight settings for each of four observers. ● (motion): as the duty cycle increased from 0.05 to 0.45 the apparent speedup dropped from 30.1 to 1.5%. The temporal frequency of this stimulus was always 3.0 Hz, thus, this graph intersects with Fig. 3 at a duty cycle of 0.25. It was not possible to measure the speedup for duty cycles greater than 0.5, but we would expect it to decrease with increasing duty cycle as shown by the dotted line. ○ (flicker): when one of the spots was covered up, the apparent speedup in the flicker of the $\mathrm{AM}_{\mathrm{ISI}}$ spot dropped from 22.3% at a duty cycle of 0.05 to 1.7% at a duty cycle of 0.45. When the duty cycle of the flickering spot was increased above 0.5, the apparent flicker rate was even slower falling to 20% slower than $\mathrm{AM}_{\mathrm{no\ ISI}}$ at a duty cycle of 0.95.

temporal frequencies between 1.5 and 7.5 Hz ($F[7, 28] = 0.62$, $P > 0.05$).

The fall off in apparent speedup above 7.5 Hz may be due to an increase in the difference threshold at higher frequencies. Mandler (1984) found that the difference threshold for a 1 deg flickering spot was fairly constant (10%) below 7.5 Hz, but increased above 7.5 Hz. Our 10.3% speedup is approximately one difference-threshold step for frequencies between 1.0 and 7.0 Hz, but less than one step for higher temporal frequencies. Thus, unless the percentage speedup increased at frequencies above 7.5 Hz, it would not be detectable according to Mandler's data.

The apparent speedup in flicker rate is significantly lower than the 18.6% apparent speedup of motion observed in Expt 1 ($F[1, 4] = 17.84$, $P < 0.05$) except at 5.0 Hz ($F[4, 16] = 0.05$, $P > 0.05$). This result suggests that the fall off in apparent speedup at 5.0 Hz observed in Expt 1 occurred because observers responded to the subjective flicker speed of each spot when the motion percept became poor.

Speedup as a function of duty cycle. Percentage apparent speedup as a function of the duty cycle of the flickering spot is shown in the lower regression line of Fig. 4 (open circles). The apparent speedup at duty cycles above 0.5 is negative because these stimuli appeared to flicker more slowly than the standard, which had a duty cycle of 0.5. As the duty cycle was increased from 0.05 to 0.95, the subjective flicker rate decreased linearly from + 22.3% to − 16.9%.

Although the apparent speedup in flicker rate increased with decreasing duty cycle, the flicker did not speed up as much as the motion did ($F[1, 4] = 12.70$, $P < 0.05$). In fact the perceived speedup when apparent motion was seen between two spots was almost twice the flicker speedup of each stationary spot (motion = 1.8 × flicker in Fig. 3, or 1.5 × flicker in Fig. 4). These results are consistent with a motion speedup based on the summation of the speedups within each flickering spot. However, we cannot exclude the possibility of a motion-specific speedup in addition to the flicker speedup. Anstis *et al.* (1985) found that adaptation to 3.5 Hz apparent motion, produced by two stationary spots flickered in counterphase, suppressed the perception of motion, but adaptation to 3.5 Hz in-phase flicker produced little suppression. This suggests that the perception of motion requires relative temporal phase information and we do not know if the flicker channels process phase information.

Whichever possibility is true, the motion and flicker pathways seem to have different low-pass filter characteristics. Motion sensitivity and motion speedup cut off at 4.5 Hz. Flicker speedup cuts off at 7.5 Hz (Fig. 3), but flicker sensitivity as measured by the critical fusion frequency is much higher. When motion perception fails above 4.5 Hz, the two spots, which are really flickering in counterphase, look as though they are flickering in phase. Thus the temporal phase information needed for motion perception is lost before the amplitude information necessary for flicker perception. Also, above 4.5 Hz the motion speedup falls to the same level as the flicker speedup (Fig. 3).

Returning now to motion, we shall test an explanation of motion speedup in terms of a hypothetical "velocity saturation".

Experiment 3: why does the subjective speed of apparent motion vary inversely with duty cycle?

The speedup is caused by the shorter on-time and not by velocity saturation. A spot in apparent motion jumps between fixed positions and is alternately visible (and stationary) during the on-times, and invisible during the ISIs. We now ask whether the spot gets speeded up during the on-times or during the ISIs. Figure 5a shows the space-time graph of a spot in real motion. The velocity of this spot is equal to the slope, as shown in Fig. 5d, and is obtained by differentiating position over time. A spot in apparent motion is represented in Figs 5b and c. Apparent motion without an ISI is shown in Fig. 5b and with an ISI in Fig. 5c. (The change in direction of the actual stimuli used in our experiments has been ignored to simplify the explanation.) Because the velocity of a spot in real motion is given by the slope of the line in Fig. 5a, one might expect that the perceived velocity of a spot in apparent motion would be given by the mean slope of the staircases in Figs 5b and c (shown in Figs 5e and f), but this cannot be the whole story because Expt 1 showed that the apparent motion looks faster with ISIs (Fig. 5c) than without (Fig. 5b) although both stimuli have the same mean slope. What can be altering the perceived slope?

The space-time graph of $AM_{\text{no ISI}}$ (Fig. 5b) resembles a staircase in which the horizontal treads depict the spot at successive positions and the vertical risers, shown by the dotted lines, depict the spot as it moves invisibly from one

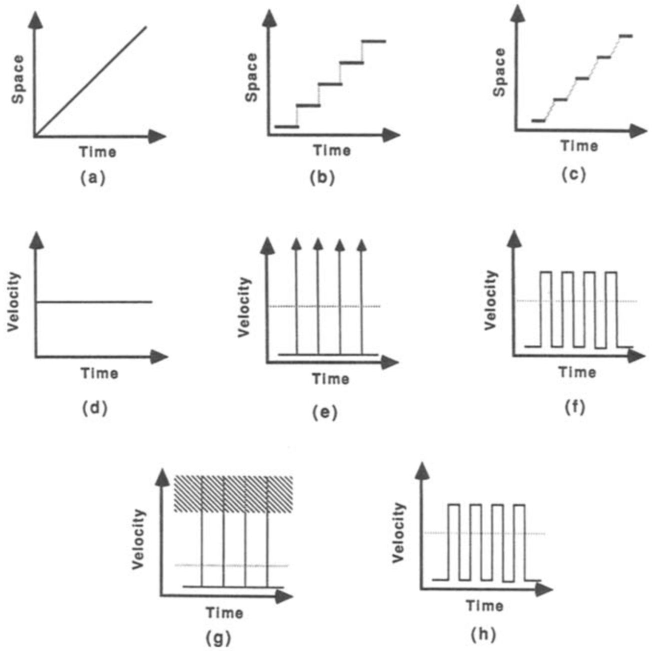

Fig. 5. A velocity-saturation model of the apparent speedup: the motion of an object may be represented graphically by plotting its position with respect to time: (a) real motion, (b) $\mathrm{AM}_{\mathrm{no\ ISI}}$, and (c) $\mathrm{AM}_{\mathrm{ISI}}$. The dotted lines in (b) and (c) indicate spatiotemporal interpolation while the object changes position. A velocity function for each type of motion is obtained by plotting the **change** in position with respect to time: (d) real motion with constant velocity, (e) $\mathrm{AM}_{\mathrm{no\ ISI}}$ with infinite velocity when the object changes position, and (f) $\mathrm{AM}_{\mathrm{ISI}}$ with finite velocity during the ISI. The time-averaged velocities are indicated by the dotted horizontal lines in (e) and (f). If we assume that the velocity detector saturates at high velocities [as shown by the hatched area in (g)], then only the extremely high interpolated velocities in (e) are clipped, not those in (f), and the time- averaged effective velocity of $\mathrm{AM}_{\mathrm{no\ ISI}}$ (g) becomes lower than that of $\mathrm{AM}_{\mathrm{ISI}}$ (h). However, the results of Expt 3 (Fig. 6) tell against this model.

position to the next. With an ISI (Fig. 5c) the treads are shorter and the dotted lines are sloping instead of vertical.

Two factors might be speeding up the $\mathrm{AM}_{\mathrm{ISI}}$. The speedup might occur while the spot is invisible. The velocity of the spot is correctly interpolated if there is an ISI (oblique dotted lines in Fig. 5c), but when there is no ISI (vertical dotted lines in Fig. 5b) the effective velocity is infinite, so it is underestimated by the visual system. All sensory systems saturate when confronted with an effectively infinite stimulus, so it is highly likely that the differentiator would do so, acting as a filter with some kind of compressive nonlinearity that would clip the high interpolated velocities in $\mathrm{AM}_{\mathrm{no\ ISI}}$ (Fig. 5g), but pass the low velocities in $\mathrm{AM}_{\mathrm{ISI}}$ (Fig. 5h). Thus, $\mathrm{AM}_{\mathrm{ISI}}$ would have a higher effective velocity than $\mathrm{AM}_{\mathrm{no\ ISI}}$. In other words, the posited nonlinearity in the motion detectors leads to a breakdown in velocity-time reciprocity. We will call this the velocity saturation hypothesis. Cavanagh and Anstis (1986) attributed a brightness shift in moving ramp stimuli to a similar saturation nonlinearity in the visual response to changing luminance.

Alternatively, the speedup might occur while the spot is visible, with the on-time at each position, the horizontal risers, providing visual evidence of stationariness. The on-time is shorter, and thus the spot is less stationary, when there is an ISI (Fig. 5c), and this might speed up the perceived velocity.

To test the velocity saturation hypothesis, a central spot halfway along the motion path was introduced during the ISI (Fig. 2d). This yielded a stimulus with the same on-time for each spot as $\mathrm{AM}_{\mathrm{ISI}}$ but with the same input to the hypothetical velocity detector as $\mathrm{AM}_{\mathrm{no\ ISI}}$ (as in Fig. 5b). The temporal frequency for this 3-spot standard was 3.0 Hz, with no ISIs. Since the central spot was illuminated twice in a cycle, each spot had an on-time of 84 msec (Fig. 6a). PSEs were obtained for two different comparison stimuli:

2-spot ISI comparison. The duty cycle of this comparison was fixed at 0.25. This stimulus was identical to the standard with the middle LED occluded (Fig. 6b).

2-spot no ISI comparison. The duty cycle of this comparison was fixed at 0.5 (Fig. 6c).

The ISI comparison was judged to move at the same speed as the standard ($t[3] = -0.18$, $P > 0.5$), while the no ISI comparison was judged to move 17% slower than the standard ($t[3] = 13.3$, $P < 0.005$). These results are evidence against the saturation hypothesis because they show that the on-time rather then the ISI is responsible for subjective speed. The 2-spot ISI comparison and the 3-spot standard had the same on-time and were perceived to move at the same speed, while the 2-spot no ISI comparison with a longer on-time was perceived to move more slowly. The absence of an ISI did not slow down the apparent motion, thus, the ISI itself is not important. The subjective speed of AM seems to be determined by the on-time of a spot. The shorter the time a spot is visible in each position along its motion path, the faster its subjective speed.

The speedup is not due to a difference in subjective spatial separation. In Expt 1, observers sometimes reported that the stimuli appeared to travel different distances during the two intervals. It is not known if AM_{ISI} or $AM_{no\ ISI}$ was systematically overestimated, since the randomization procedure blinded both the experimenter and the observer to the actual order and position of each AM stimulus, but this difference in subjective spatial separation might perhaps be altering the subjective speed.

In the tau effect (Helson, 1930; Geldreich, 1934), the distance between a pair of lights separated by a long ISI appears to be greater than the distance between the same pair of lights separated by a short ISI (Jones and Huang, 1982). Thus, it is possible that the spatial separation of AM_{ISI} appears to be greater than the spatial separation of the limiting case, $AM_{no\ ISI}$, in which the ISI is zero. Physical speed and physical spatial separation are directly proportional. Similarly, subjective speed and subjective spatial separation might be directly proportional; the speed of AM might look faster when the spatial separation looks larger.

To keep the observers' task consistent with the other experiments, we compared the subjective speeds of two $AM_{no\ ISI}$ stimuli differing in spatial separation by 1 deg, rather than measuring the subjective spatial separation of AM_{ISI} and $AM_{no\ ISI}$. (All observers agreed that a 1 deg difference was larger than the difference in subjective separation observed in Expt 1.) We found that observers judged the speed of a 1 deg, 3 Hz $AM_{no\ ISI}$ stimulus to be equal to the speed of a 2 deg, 3 Hz $AM_{no\ ISI}$ stimulus ($t[3] = 1.05$, $P > 0.25$). Increasing the spatial separation did not produce a motion speedup, thus, the greater subjective speed of AM_{ISI} compared with $AM_{no\ ISI}$ cannot be due to a difference in subjective spatial separation. The implications of this finding for the computation of subjective speed will be considered in the General Discussion.

The speedup is not due to a difference in time-averaged luminance. Another hypothesis was that the difference in the time-averaged luminance of AM_{ISI} and $AM_{no\ ISI}$ was responsible for the difference in subjective speed. The two AM configurations obviously have different temporal luminance profiles. Thus, al-

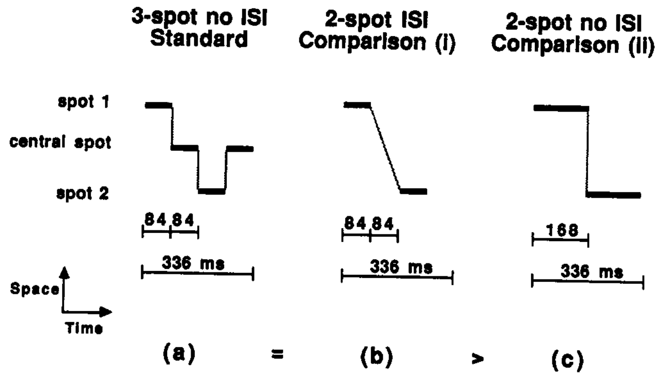

Fig. 6. This space-time diagram shows the stimuli used in Expt 3. The dotted lines indicate interpolated velocities. Results: (a) and (b) had the same subjective speed, but (c) looked slower, thus the speedup results from a short on-time [in (a) and (b)], not from the presence of an ISI [in (b) only]. These results provide evidence against the velocity-saturation model pictured in Fig. 5.

though their maximum and minimum luminances are the same, the on-time of $AM_{no\ ISI}$ is double that of AM_{ISI}. According to Bloch's law, the perceptual effect of a stimulus depends on the product of on-time and luminance, for on-times below some critical value (Kahneman and Norman, 1964; Brown, 1955). Kahneman *et al.* (1967) have shown that this critical value depends on the experimental task. For low-level tasks, such as brightness discrimination, the critical duration is approx. 100 msec, while for higher-level tasks, such as form resolution (and possibly motion perception), it may be as high as 350 msec.

Since the on-times used in Expt 1 were all shorter than 350 msec Bloch's law may hold and the time-averaged luminance of the stimuli might affect their subjective speed. However, this hypothesis was rejected because we found that the percentage speedup remained the same even when the time-averaged luminances of the stimuli were equated. AM_{ISI} with a luminance of 600 cd/m^2, an on-time of 84 msec, and an ISI of 84 msec, was still judged to be 18.6% faster than $AM_{no\ ISI}$ with a luminance of 300 cd/m^2, and an on-time of 168 msec.

Thus, the subjective speed of apparent motion does not depend on the length of the ISI, nor on the subjective spatial separation, nor on the time-averaged luminance of the stimuli, rather the on-time is the important variable. In the remaining experiment we investigated the nature of this on-time dependence in more detail.

Experiment 4: an ISI while the spot is stationary does not speed up apparent motion

An AM spot has zero speed while it remains in one position, and we have found in Expt 3 that the longer the spot remains in one position (i.e. the longer its on-time), the slower it appears to move. In the previous experiments, the spot appeared in one position then disappeared and reappeared in a new position. With such a stimulus, it is impossible to know whether the visual system responds to the length of time for which a particular set of receptors is stimulated by the spot, or to the time between the onset and offset of the spot in each position.

In the experiment, we tested these two possibilities by comparing the subjective speed of a spot that was visible at the beginning and end of its "duration" with that of a spot that was continuously visible for the same duration. These stimuli should appear to move at the same speed if the on-time is signalling the **time for which a spot has zero speed** along its motion path.

The pattern of LEDs and the time course of the stimuli are shown in Fig. 2d and Fig. 7 respectively. Each LED in the double-flash standard sequence (Fig. 7a) was flashed for 5 msec at the beginning and the end of a 100 msec on-time, and then a 100 msec ISI elapsed before the next LED was flashed. Each LED in the full-duration comparison sequence was on continuously for a 100 msec on-time, then an ISI equal to this on-time elapsed before the next LED was illuminated (Fig. 7d). We also measured the subjective speeds of two control stimuli. Each LED in the single-flash (3-spot) standard sequence was flashed once and then an ISI elapsed before the next LED was flashed. This standard differed from the double-flash standard in that rather than flash the same LED for a second time, a spatially intermediate LED was flashed (Fig. 7b). Finally, in the single-flash (2-spot) standard sequence, each LED was flashed once and then an ISI, equal to twice the ISI of the single-flash (3-spot) sequence, elapsed before the next LED was flashed (Fig. 7c). The temporal frequency of the full-duration comparison was varied to obtain a match in subjective speed with the three standards.

The double-flash standard (a) was judged to move at the same speed as the full-duration comparison (d) ($t[3] = 0.28, P > 0.25$), while the single-flash 3- and 2-spot standards (b,c) were judged to move 20% ($t[3] = 9.59, P < 0.005$) and 26% ($t[3] = 5.43, P < 0.01$) faster than the full-duration comparison. The apparent speed-up of the single-flash standards (b, c) was significantly faster than that of the double-flash standard (a) with a longer signalled on-time ($F[1, 6] = 57.2, P < 0.01$). The subjective speeds of the single-flash standards (b, c), both with on-times of 5 msec, did not differ significantly from each other ($F[1, 6] = 3.6, P > 0.05$). Thus, an ISI while the spot is stationary does not speed things up, but an ISI separating a change in position increases the subjective speed of apparent motion. It is the time for which the stimulus appears to remain in one position that is important, and not the continuous stimulation of a particular retinal area.

GENERAL DISCUSSION

We have found that apparent motion with an ISI is subjectively faster than apparent motion without an ISI. AM_{ISI} with a duty cycle of 0.25

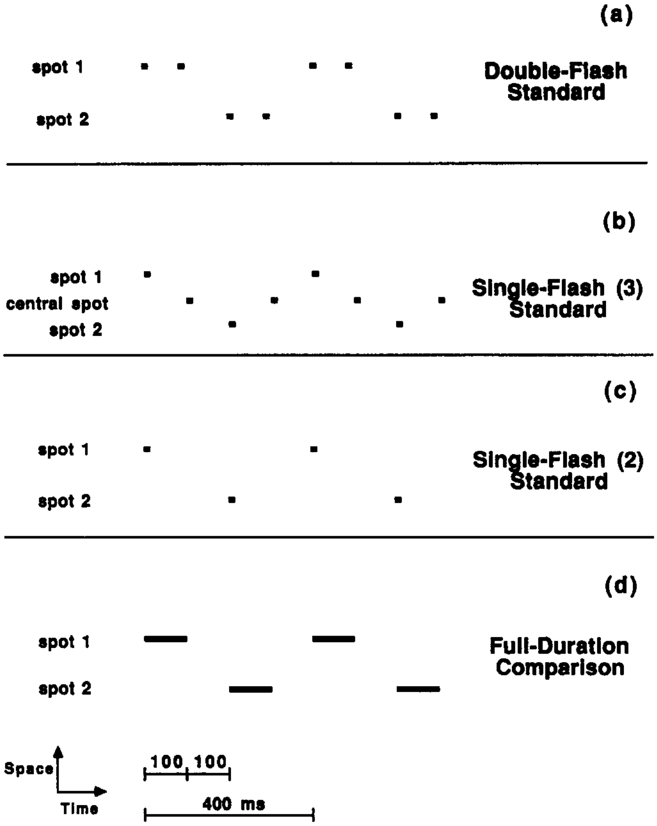

Fig. 7. This space-time diagram shows the stimuli for Expt 4. Results: (a) and (d) appeared to move at the same speed, while (b) and (c) appeared to move faster. Therefore, the ISI while the spot was stationary in (a) did not speed things up compared with (d), so (a) and (d) had the same effective on-time. This suggests that on-time is important only in so far as it signals the time for which the spot has zero speed.

is a constant 18.6% faster than $AM_{no\ ISI}$ with a duty cycle of 0.5, at temporal frequencies between 1.5 and 4.5 Hz. A similar flicker speedup effect is obtained when one of the AM spots is covered up, but the flicker effect is smaller (only 10.3%) and it persists at frequencies above 4.5 Hz. As the duty cycle of AM_{ISI} decreases from 0.45 to 0.05, the subjective speedup in motion increases linearly from 1.5 to 30.1%, while the subjective speedup in flicker rate increases linearly from 1.7 to 22.3% relative to a standard duty cycle of 0.5.

We do not know whether the difference between motion and flicker arises (a) because the motion channels are fed by the flicker channels, thus motion speedup is a summation of the apparent flicker rates of the two stationary spots, or (b) because the motion speedup is a motion-specific effect over and above the flicker speedup. We found in Expt 3 (p. 341) that doubling the spatial separation between spots did not affect the subjective speed of motion, therefore speed might be computed purely temporally with no spatial component. The perceived temporal frequency, and thus the subjective speed, is faster for shorter on-times. Sekuler *et al.* (1978) summarize physiological and psychophysical evidence that many aspects of the response of motion-sensitive mechanisms are determined by the temporal frequency rather than the velocity of moving spatially periodic stimuli. However, we have no objective measure of which percept is used to judge the speed of motion. It could be the perceived temporal frequency of the change in position of the spot, or the perceived temporal frequency of the flicker in each position that determines the subjective speed of AM.

It was shown in Expts 3 and 4 that the subjective speed of AM depends on the on-time of the stimulus and not on the duration of the off-time or ISI. The longer the on-time, the slower the subjective speed of movement. The stimulus need not remain visible throughout its on-time. An equivalent subjective speed is obtained by briefly flashing the stimulus at the beginning and the end of each on-time. From this we hypothesize that the on-time is signalling the time for which the spot has zero speed.

Why should the subjective speed of AM be determined by the time for which the object does **not** appear to move? Braddick (1974) has demonstrated quite convincingly that the motion-detecting system includes two distinct processes, a low-level short-range process which may be identified with the directionally selective neurons of the visual system, and a higher-level long-range process of a more interpretive nature. The short-range process is dominant for AM stimuli with spatial separations less than 15 min, ISIs less than 100 msec (with 100 msec on-time), dark ISIs, and monocular presentation. The long-range process is dominant for stimuli with larger spatial separations, longer ISIs, bright or dark ISIs, and dichoptic or monocular presentation. The two processes may work together, with the information from the short-range process placing constraints on the interpretation that the long-range process can select. For example, when observers are presented with the stimulus in Fig. 8a (Ternus, 1926), they may perceive either the outer line moving back and forth across two stationary central lines, or all three lines moving back and forth as a group. The former perception of "element movement" predominates under conditions that activate the short-range process, while the latter perception of "group movement" predominates when the long-range process is activated (Pantle and Picciano, 1976; Braddick and Adlard, 1978).

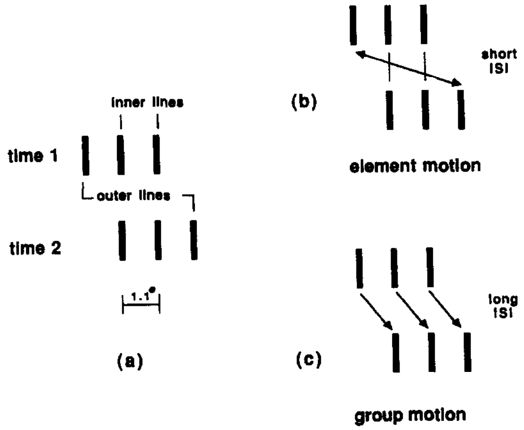

Fig. 8. (a) The configuration used by Ternus (1926), Pantle and Picciano (1976) and Braddick and Adlard (1978). (b) Element movement—the outer line appears to move back and forth. (c) Group motion—all three lines appear to move back and forth together. Presumably, the short-range motion process promotes element movement while the long-range process promotes group movement.

However, the spatial displacement that is perceived in element movement is at least 10 times greater than the spatial limit of the short-range process. Braddick and Adlard (1978) suggested that, in the case of element movement, the short-range process signals that the **inner** lines are stationary. They showed that when the inner lines are dichoptic and the outer lines are monocular and thus the short-range process is not activated, group movement predominates, but when the outer lines are dichoptic and the inner lines are monocular and thus activate the short-range process, element movement predominates. They concluded that the short-range process is responsible for the perception of element movement because it signals "no movement" of the inner lines of the display.

We suggest that in our experiments, as well, the short-range process signalled **no** movement. The *presence* of motion must be sensed by the long-range process because the spatial and temporal parameters of the stimuli fall outside the limit for the short-range process. However, if the short-range process signalled the *absence* of movement in the stimulus, then the time for which there was no movement, the on-time, would be important for determining the speed of movement. Thus, we have found that it is not a short off time that speeds things up but a long on-time that slows things down.

We can also describe our results in the Fourier domain. The Fourier series and spectra for the flickering stimuli are shown in the Appendix. It is true that reducing the duty cycle of a flickering spot from 0.5 (square wave) to 0.05, introduces twice as many harmonics. A pulse train with a small duty cycle contains more harmonics than a square wave does (a square wave contains only odd harmonics whose amplitudes fall off rapidly with increasing frequency). This might tempt one to attribute the large flicker speedup at small duty cycles to the higher harmonics, but we believe that this attribution would be quite incorrect. Consider the case of two flickering spots with complementary duty cycles of 0.05 and 0.95. The former looks about 47% faster than the latter, yet one waveform is the inverse of the other. They have identical Fourier spectra except for the component at zero temporal frequency which has an amplitude of 0.95 for the 0.95 duty cycle, and 0.05 for the 0.05 duty cycle. Hence the difference in perceived flicker rate can have nothing to do with the higher harmonics, which are identical, but must lie in the zero frequency component. Thus, it is not that high frequencies speed things up, but that low frequencies slow things down. The longer the duty cycle, the larger the zero frequency component, and the slower the subjective speed.

The finding that AM_{ISI} looks faster than $AM_{no\ ISI}$ is consistent with our earlier measures of adaptation to apparent motion (Anstis *et al.*, 1985) in which we compared these two types of AM. The perception of motion degenerates into the perception of flicker following prolonged inspection of an AM stimulus. Observers were adapted to one type of AM and the probability of seeing motion, as opposed to flicker, was measured on the other type of AM. AM_{ISI} was found to be less adaptable and was a more effective adaptor than $AM_{no\ ISI}$. We called this aspect of the stimulus "motion strength"; AM_{ISI} provides a stronger motion signal than $AM_{no\ ISI}$ of the same temporal frequency. Subjective speed may be another way in which motion strength is revealed. The stronger motion stimulus, AM_{ISI}, looks faster or more dynamic.

Finally, we would like to suggest a possible physiological substrate for the short-range motion process. Orban *et al.* (1981) classify cells in areas 17 and 18 of cat visual cortex into one of four categories according to their velocity preferences: velocity low-pass which respond very well to low velocities and have a peak upper cutoff velocity below 20 deg/sec, velocity high-pass cells which have a response increasing as a power function of velocity from a threshold of 4 deg/sec to a saturation velocity of 150 deg/sec, velocity tuned cells which respond to a restricted range of velocities around an optimum, and velocity broad-band cells which respond over a wide range of velocities with no optimum. They suggest that the low-pass cells are involved in the analysis of stationary visual objects because the mean velocity of slow drifts of the eyes during fixation in the unparalyzed cat corresponds to the slowest velocity giving a peak response in the paralyzed cat. It is these low-pass cells that we suggest may be identified with the short-range motion process, which also signals no movement under certain conditions.

Our conclusion that the on-time of a moving stimulus determines its subjective speed is supported by the finding that the velocity preference of a given cell in area 17 can be predicted by its threshold stimulus duration (Duysens *et al.*, 1984), with the velocity low-pass cells responding to long stimulus durations and the velocity high-pass cells responding to short stimulus durations.

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REFERENCES

Anstis S., Giaschi D. and Cogan A. (1985) Adaptation to apparent motion. *Vision Res.* **25,** 1051–1062.

Beck J. and Stevens A. (1972) An aftereffect to discrete stimuli producing apparent motion and succession. *Percept. Psychophys.* **12,** 482–486.

Braddick O. J. (1974) A short-range process in apparent motion. *Vision Res.* **14,** 519–526.

Braddick O. J. and Adlard A. (1978) Apparent motion and the motion detector. In *Visual Psychophysics and Physiology* (Edited by Armington J. C., Krauskopf J. and Wooten B. R.), pp. 417–426, Academic Press, New York.

Brown R. H. (1955) Velocity discrimination and the intensity-time relation. *J. opt. Soc. Am.* **45,** 189–192.

Caelli T. and Finlay D. (1981) Intensity, spatial frequency, and temporal frequency determinants of apparent motion: Korte revisited. *Perception* **10,** 183–189.

Cavanagh P. and Anstis S. (1986) Brightness shift in drifting ramp gratings isolates a transient mechanism. *Vision Res.* **26,** 899–908.

Cornsweet T. (1962) The staircase-method in psychophysics. *Am. J. Psychol.* **75,** 485–491.

Duysens J., Orban G. A. and Cremieux J. (1984) Functional basis for the preference for slow movement in area 17 of the cat. *Vision Res.* **24,** 17–24.

Gaito J. (1973) *Introduction to Analysis of Variance Procedures.* MSS Information Corporation, New York.

Geldreich E. W. (1934) A lecture room demonstration of the visual tau effect. *Am. J. Psychol.* **46,** 483.

Helson H. (1930) The tau-effect: An example of psychological relatively. *Science N. Y.* **71,** 536–537.

Jones B. and Huang Y. L. (1982) Space-time dependencies in psychophysical judgement of extent and duration—Algebraic models of the tau and kappa effects. *Psych. Bull.* **91,** 128–142.

Kahneman D. and Norman J. (1964) The time-intensity relation in visual perception as a function of observer's task. *J. exp. Psychol.* **68,** 215–220.

Kahneman D., Norman J. and Kubovy M. (1967) Critical duration for the resolution of form: Centrally or peripherally determined? *J. exp. Psychol.* **73,** 323–327.

Kaufman L., Cyrulnick I., Kaplowitz L., Melnick G. and Stof D. (1971) The complementarity of apparent and real motion. *Psychol. Forsch.* **34,** 343–348.

Kolers P. A. (1972) *Aspects of Motion Perception.* Pergamon Press, New York.

Mandler M. B. (1984) Temporal frequency discrimination above threshold. *Vision Res.* **24,** 1873–1880.

McKee S. (1981) A local mechanism for differential velocity detection. *Vision Res.* **21,** 491–500.

Orban G. A., Kennedy H. and Maes H. (1981) Response to movement of neurons in areas 17 and 18 of the cat: velocity sensitivity. *J. Neurophysiol.* **45,** 1043–1058.

Pantle A. and Picciano L. (1976) A multistable display: evidence for two separate systems in human vision. *Science N. Y.* **193,** 500–502.

Sekuler R. W., Pantle A. and Levinson E. (1978) Physiological basis of motion perception. In *Handbook of Sensory Physiology VIII* (Edited by Held R., Leibowitz H. and Teuber H. L.), pp. 67–96. Springer, Berlin.

Taylor M. M. and Creelman C. D. (1967) PEST: efficient estimates on probability functions. *J. acoust. Soc. Am.* **41,** 782–787.

Ternus J. (1926) Experimentelle Untersuchungen uber phänomenale Identitat. *Psychol. Forsch.* **7,** 81–136. Excerpted and translated as: The problem of phenomenal identity (1938) In *A Source Book of Gestalt Psychology* (Edited by Ellis W. D.), pp. 149–160, Routledge, London.

Tyler C. W. (1973) Temporal characteristics in apparent movement: omega movement vs phi movement. *Q. Jl exp. Psychol.* **25,** 182–192.

APPENDIX

The Fourier Spectra of the Flickering Stimuli

The stimuli used in this paper have been described in the time domain, but a Fourier-domain description will be given here. A flickering spot, as used in Expt 2, consists of a temporal train of identical rectangular pulses of magnitude A and duration d, and may be represented by the periodic function $f(t)$. Over one period:

$$f(t) = \begin{cases} A & 0 < t < d \\ 0 & -T/2 < t < 0, d < t < T/2 \end{cases}$$

(T is the period in seconds.)

This function can then be represented by the trigonometric Fourier series:

$$f(t) = \frac{1}{2}a_0 + \sum_{n=1}^{\infty} [a_n \cos(n\omega_0 t) + b_n \sin(n\omega_0 t)] \quad \omega_0 = \frac{2\pi}{T}$$

where the Fourier coefficients a_n and b_n of $f(t)$ are defined as follows:

$$\frac{1}{2}a_0 = \frac{1}{T}\int_{-T/2}^{T/2} f(t)\,\mathrm{d}t = \frac{1}{T}\int_0^d A\,\mathrm{d}t = \frac{Ad}{T};$$

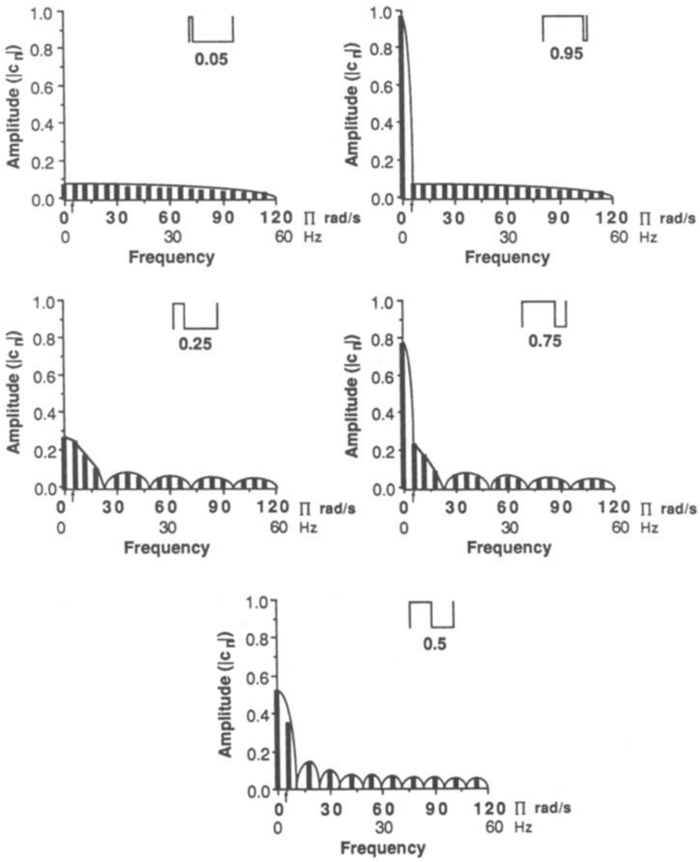

Fig. 9. The Fourier amplitude spectrum for five of the flickering stimuli used in Expt 2. The waveform in the upper right corner of each graph represents the duty cycle. The fundamental frequency (f) was 3 Hz in each case. It can be seen that the spectrum flattens out as the duty cycle moves away from 0.5 in both directions.

$$a_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\cos(n\omega_0 t)\,\mathrm{d}t;$$

$$= \frac{2}{T}\int_{0}^{d} A\cos(n\omega_0 t)\,\mathrm{d}t;$$

$$= \frac{A}{n\pi}\sin\frac{(2n\pi d)}{T};$$

$$b_n = \frac{2}{T}\int_{-T/2}^{T/2} f(t)\sin(n\omega_0 t)\,\mathrm{d}t;$$

$$= \frac{2}{T}\int_{0}^{d} A\sin(n\omega_0 t)\,\mathrm{d}t;$$

$$= \frac{-A}{n\pi}\left(\cos\frac{(2n\pi d)}{T} - 1\right);$$

$$f(t) = \frac{Ad}{T} + \frac{A}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\sin\frac{(2\pi nd)}{T}\cos\frac{(2\pi nt)}{T}$$

$$-\left(\cos\frac{(2\pi nd)}{T} - 1\right)\sin\frac{(2\pi nt)}{T}.$$

Thus, the Fourier series representation describes a flickering light as a sum of sinusoidal components (harmonics) with frequencies n times the fundamental frequency, ω_0.

The magnitude of the harmonic amplitudes is given by the equation:

$$|c_n| = \tfrac{1}{2}\sqrt{a_n^2 + b_n^2};$$

$$= \frac{1}{2}\sqrt{\frac{A^2}{n^2\pi^2}\left[\left(\sin 2\frac{(\pi nd)}{T}\right)^2 + \left(1 - \cos 2\frac{(\pi nd)}{T}\right)^2\right]};$$

$$= \frac{A}{n\pi}\sin\frac{(n\pi d)}{T}.$$

The amplitude spectrum is obtained by plotting $|c_n|$ vs the discrete frequency $n\omega_0$. For $T = 1/3$ sec(3 Hz), $\omega = 0$, 6π, 12π, $18\pi, \ldots$ This spectrum is shown in Fig. 9 for five of the duty cycles used in Expt 2 (duty cycle $= d/T$). The fundamental frequency (f) was 3 Hz in all cases.

It can be seen that the spectrum flattens out as the duty cycle moves away from 0.5 in both directions. The only aspect of the spectrum that increases with increasing duty cycle is the **amplitude of the zero frequency component**. Thus, it seems that it is the power in the zero frequency component that determines the subjective speed.