a photocell and an oscilloscope to monitor the display and to verify that the program is generating the intended number of frames in the intended sequence.

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NOTE

1. There is no conventionally agreed upon photometric term for the integral of luminous intensity (LeGrand, 1968; Walsh, 1953); it is the *quantity of light* per solid angle, emitted in a particular direction. Possible units are (lumens $\times$ seconds)/steradian, talbots/steradian, and candles $\times$ seconds. Integrated luminous intensity is perhaps the most accurate name, but luminous directional energy better carries the meaning in the present context. In any case, the choice of units (candles $\times$ microseconds) makes it perfectly clear what is being measured.

Flicker in computer-generated visual displays: Selecting a CRO phosphor and other problems*

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The visual system's response to flicker is approximated by 6-9 RC stages in series. The CRO phosphor can be represented by one additional RC stage. Therefore, increasing the refresh rate by a factor of k can be k^5 to k^8 times more effective in reducing apparent flicker than increasing the phosphor time constant. "Slow" phosphors impair the display of rapid movement and cause undesirable persistence of old picture contents after they have been altered. Behavioral scientists usually should choose fast, efficient phosphors. Display programs should be written so that spatially adjacent points of a display are intensified as close together in time as possible.

A visual display on a cathode ray oscilloscope is composed of points, vectors, characters, or scan lines. A single picture (*frame*) can be *painted* in a relatively short time, depending, of course, on the number of elements of which it is composed, as elements are painted sequentially. In order to give the viewer the illusion that the display is present continually, the frame must be repainted (*refreshed*) about 20 to 40 times per second. The more frequently it is refreshed, the less it appears to flicker.

In contemporary CRO displays, each individual point (of a frame) typically is electronically pulsed (*intensified*) for 1 microsec or less. At a refresh rate of 40 frames/sec, the point will be reintensified 40 times per second, i.e., every 25 msec. The transduction of the electron intensification beam to light is accomplished by a *phosphor* painted on the inside of the CRO tube.

Depending on the particular phosphor, the light output in response to the brief intensification pulse may either persist long after the pulse or it may follow the shape of the intensification pulse. The phosphor is a means of prolonging, or "spreading out," the light in time and thereby reducing the apparent flicker.

The light output of a phosphor in response to an exceedingly brief intensification pulse (*impulse*) typically follows an exponential curve of the form illustrated in Fig. 1. This exponential decay curve is characterized by a single parameter, its decay time constant (τ), which is defined as the time taken to decay to .368 of the initial value.¹ When the time constant is long, apparent flicker is minimized; when it is short, flicker is maximized.

THE PHOSPHOR PROBLEM: FAST OR SLOW?

In "continuous" CRO displays it is desirable to minimize apparent flicker. This could be accomplished either by (1) choosing a phosphor with a long time constant (a "slow" phosphor), or by (2) increasing the refresh rate.

One disadvantage of choosing a phosphor with a long time constant is that it makes the display system

unsuitable for applications requiring brief visual presentations, because brief exposures are impossible with slow phosphors. Furthermore, when the display contents are altered, a slow phosphor causes the old contents to persist visibly under the new picture. This difficulty makes slow phosphors unsuitable for presenting rapid motion.

Alternatively, apparent flicker can be reduced by increasing the refresh rate. However, it may be impossible to increase the refresh rate when frames are composed of large numbers of points or characters. Even when it is possible, a high refresh rate places an added burden on the computer. The following sections evaluate these factors in terms of the flicker sensitivity of the human visual system. The conclusion (for behavioral scientists) will be that phosphors with short time constants should be chosen, except when display systems are dedicated to static displays.

Flicker Sensitivity of the Visual System

The response of the visual system to flickering light can be predicted from the model illustrated in Fig. 2. It is a good first-order mathematical approximation to a more complicated model (Sperling & Sondhi, 1968) in the frequency range of interest, i.e., for frequencies ≥ 10 Hz. The basic elements of this approximation are RC stages, linear elements whose response to an impulse input is an exponential output of the form already described in Fig. 1.²

In the dark, the response of the visual system to flicker can be represented by three RC stages in series (each having a time constant of about 25 msec) plus six more RC stages in series (each having a time constant of about 5 msec). In very bright light, the visual system's response to flicker is represented simply by the final six stages (each with $\tau = 5$ msec). That is, in very

Fig. 1. Light response of a phosphor to an intensification impulse (theoretical). Ordinate: light output; abscissa: time; the intensification impulse is indicated below. The response illustrated is an exponential decay function with a time constant of τ .

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Fig. 2. First-order linear approximation to the visual system's response to flicker. There are nine RC stages in series in two sets; for all stages within a set τ ($= RC$) is the same. The value of τ_1 is 25 msec in the dark, 5-25 msec at room illuminations, and less than 5 msec in extremely intense light. The value of τ_2 is constant and equal to about 5 msec. When the input stimulus is a pulsed flickering light, as illustrated, the flicker in the response is markedly reduced. Here, only the first Fourier component is visible. (After Sperling & Sondhi, 1968.)

bright light, the time constant of the initial three stages becomes so small that it is negligible. At intermediate light levels (e.g., room illumination), the initial three stages can be assumed to have time constants between 5 and 25 msec, depending on the intensity of the illumination and on many other factors.

Except in very dim light, the visual system has what engineers would call excellent *gain control*. That is, its response is proportional to the percent of flicker (relative to the steady background level) rather than to the absolute amount of flicker. The *gain control* mechanism itself begins to affect the responses to flicker at frequencies below 10 Hz; therefore, the linear model is accurate only at

frequencies of 10 Hz or higher.³ Fortunately, this covers the frequency range of interest. In this range, only the fundamental frequency of a flickering stimulus will be significant for flicker perception; higher harmonics can be neglected. Thus the effective input stimulus can be regarded as the percent modulation of the background by the fundamental frequency of the stimulus. (On this scale, the sensitivity of the visual system diminishes in dim light, but in practice this change is small relative to the change in frequency response caused by the increased time constant of the first three stages.)

If we assume impulse intensification pulses and neglect the effect of the phosphor (i.e., assume a fast phosphor), then the depth of the sinusoidal modulation produced by the refresh frequency is easily calculated: it is 200%. Impulse intensification produces effectively the same flicker as 200% modulation by a sine wave at the refresh frequency. As negative values of light are impossible, pure sinusoidal modulation is limited to 100% modulation depth, but the predictions based on the 200% fundamental component have been verified experimentally (Kelly, 1964).

The response of the visual system at typical room illuminations to flicker at frequencies greater than about 10 Hz can be summarized as follows. (1) At 10 Hz the system is extremely sensitive to flicker; a modulation of less than 1% can be detected. (2) At 20 Hz the sensitivity of the system to flicker is vastly reduced. (3) At 40 Hz the limit of detection is approached, even at 100% (or 200%) modulation. Where the limit of flicker detection lies (i.e., between 40 and 70 Hz) depends on the particular individual, the luminance level, the size and chromaticity of the flickering field, the region of the retina being used, and other factors. Some typical measurements that describe quantitatively the threshold sensitivity of the eye to sinusoidal flicker are illustrated in Fig. 3.

The Phosphor as an Added RC Stage

Mathematically, the effect of a phosphor in reducing apparent flicker is equivalent to adding a single RC stage in series to the system described above. It is immediately obvious that when the time constant of the phosphor is 5 msec or smaller, it will make no significant difference to the overall system; there are already at least six stages having a time constant of 5 msec or more. When the time constant of the phosphor is 25 msec, it can make a noticeable difference but probably not a big difference. When the time constant is 250 msec, the phosphor can reduce flicker (at refresh rates greater than about 10 Hz) by 10X relative to $\tau = 25$ msec.

The Tradeoff Between Phosphor Time Constant and Refresh Rate

The flicker reduction of an RC stage is given by its *filter* or *attenuation characteristic*. Figure 4 illustrates the attenuation characteristics (for sine waves) of a single RC stage. The "corner" or "cut-off" frequency (Fig. 4) is related to the time constant by $f_c = 1/(2\pi\tau)$. For example, when $\tau = 5$ msec, $f_c = 32$ Hz; when $\tau = 25$ msec, $f_c = 6.4$ Hz. Figure 4 shows that frequencies much larger than the cut-off frequency (high frequencies) are attenuated in direct proportion to their frequency. Equivalently, increasing τ by a factor of k ($\tau' = k\tau$) increases attenuation of high frequencies by a factor of k . It is this principle that was used to calculate the 10X reduction in flicker produced by the 10X change in time constant from 25 to 250 msec.

When there are n RC stages in series (as in the model of the visual system, the attenuation of high frequencies is proportional to k^n . Because there are effectively six to nine stages in the visual system, doubling the refresh rate can increase flicker attenuation not

Fig. 3. Threshold sensitivity of the visual system to sine-wave flickering light. Abscissa: frequency (log scale); ordinate: threshold modulation in percent of background luminance (log scale). The indicated parameter is the mean retinal illuminance in trolands of the light being modulated: 10,000 (high intensity); 100 (moderate intensity); 1 (low intensity). (After DeLange, 1958).

Fig. 4. Attenuation (filter) characteristic of a single RC stage. Abscissa: frequency f of an input sine wave relative to the cut-off frequency f_c (log scale); ordinate: amplitude of output a_o /amplitude of input a_i (log scale). The cut-off frequency f_c is related to RC by: $f_c = (2\pi\tau)^{-1}$ where $\tau = RC$.

merely by a factor of 2 but by a factor of 2^6 to 2^9 ; i.e., it can reduce flicker by 64 to 512 times. At high frequencies, doubling the refresh rate is hundreds of times more effective than doubling the time constant of the phosphor. Unfortunately, the full benefit of these tremendous attenuations occurs only at high frequencies, i.e., frequencies greater than about 30 Hz. At refresh rates between 10 and 30 Hz, the effect of an increase in rate is smaller; at still lower frequencies, other factors come into play.

Exceedingly slow phosphors—even assuming they were available—would be impractical because the old picture would persist for an exceedingly long time under the new one. The requirement that the old picture fade within a second or two would eliminate phosphors with time constants greater than about 250 msec. This limit, in turn, means that producing flicker-free (or even “low-flicker”) displays will require fairly high refresh rates, i.e., over 20 Hz. These are the very conditions in which it is far more efficient to increase the refresh rate than the time constant of the phosphor.

Behavioral scientists who use on-line visual displays frequently have only one CRO unit and many users, and some users occasionally may desire to display rapid motion or to have precise stimulus control. For these installations, the moral is: Unless the CRO display system is committed to static pictures, the reduced flicker in visual displays achievable by a slow phosphor does not justify sacrificing the stimulus control achievable with fast phosphors; i.e., by phosphors with $\tau = 5$ msec or less. A corollary is that one generally should not buy “general purpose” phosphors with time constants greater than 5 msec; these provide neither precise stimulus control nor a significant lowering of the refresh rate required for freedom from flicker.

OTHER CONSIDERATIONS

Efficiency of a Phosphor

The most important characteristics (apart from fast decay) of a phosphor for behavioral scientists are efficiency, maximum output, and durability. Efficiency refers to the efficiency of conversion of electronic energy to luminous energy. Whether a display will be bright or dim is determined by the efficiency of a phosphor, but even an inefficient phosphor can be useful if powerful electronic driving circuits (and a toleration for intense driving—“durability”) enable the

phosphor to reach a high maximum output. High output is important in experiments where a frame is painted only once, when the display is viewed in daylight or in a brightly lighted room, and when color or Polaroid filters are used with the display.

Durability refers to the susceptibility of a phosphor to “burning out” when it is pulsed intensely. Burn-out leaves a permanently inactive patch in the display surface. The burned-out patch usually is discolored, as well as being inactive. In currently available phosphors, unfortunately, efficiency and fast decay are correlated with a tendency to burn out.

Painting Sequence

Another problem arises when it takes a long time to paint a frame, that is, tens of milliseconds. The eye, even when it attempts to maintain steady fixation, makes small involuntary, saccadic movements several times per second. If some line segments of a frame happen to be painted before a movement and others after the movement, these segments will appear to lie in inappropriate spatial relations to each other—displaced by the amount of the eye movement (Sperling & Speelman, 1965). In viewing such a nominally unchanging display, segments of the display appear to jitter back and forth relative to each other. The effect is very convincing and, not infrequently, the cause is erroneously attributed to a hardware failure. Slow phosphors minimize the effect. The way to minimize the effect by software is to paint adjacent parts of a frame at the same, or nearly the same, time. For example, the dot above an *i* should be painted at the same time as the *i*; never wait until a whole line is painted to dot the *i* and cross the *ts*.

Dual Phosphors

One inexpensive method that has been tried to obtain the advantages of both a fast and a slow phosphor in the same CRO has been to use both phosphors simultaneously in the same CRO tube. These two phosphors usually are of different colors. By making the slow-decay phosphor more efficient, it will predominate in the normal viewing of static displays and thereby apparent flicker will be reduced. By use of selective color filters, either phosphor may be seen alone.

The problem with dual phosphors is that the separation achieved by the color filters is not perfect and the better the separation required, the

denser the filters must be. The denser the filters, the more inefficient is the system as a whole. An inefficient highly chromatic display is particularly undesirable for showing unrefreshed frames (one of the main uses for which a fast phosphor is required). And, even a faint residual trace from the slow phosphor can utterly defeat a fast-phosphor experiment.

The real solution to the problem of fast or slow phosphors is to have a display device with a variable-speed phosphor. The *direct view storage tube* potentially is such a device. (A DVST displays a frame continuously—without requiring refreshing—until it is “erased” by a control signal.) The DVST is the logical display device for static displays. Its widespread use today (1969) is limited only by its high cost and low spatial resolution, but we can reasonably anticipate improvement in both factors. Ultimately, we hope for DVSTs which allow selective erasure, so that the DVST will control directly the precise time for which any portion of a frame is displayed.

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NOTES

1. Common phosphors have exponential decay only to about 10%-30% of peak emission; below this, decay is slower than exponential. As apparent flicker is determined mainly by the initial decay, the exponential is a valid approximation.
2. See Sperling (1964) for an introductory discussion of linear systems, RC stages, etc., in relation to vision.
3. The linear approximation to Sperling and Sondhi's nonlinear model requires a high-pass RC stage in series with the low-pass stages. The high-pass stage improves the accuracy of the approximation at low frequencies but is an unnecessary complication for the present purpose and therefore is omitted here.