Commentary

DURATIONS OF STIMULI DISPLAYED ON VIDEO DISPLAY TERMINALS: $(n - 1)/f$ + Persistence

Bruce Bridgeman
University of California, Santa Cruz

Video display terminals (VDTs) have become the most popular apparatus for displaying stimuli in psychophysical experiments. Driven by modern desktop computers, they afford convenience and flexibility. There are dangers and limitations inherent in the technology, however. The problems include limited resolution, brightness, and contrast, as well as fixed wavelength contributions to color balance. In addition, VDT users may be susceptible to such symptoms as accommodative error (Jaschinski-Kruza, 1991; Schleifer, Sauter, Smith, & Knutson, 1990) and horizontal heterophoria (Dain, McCarthy, & Chan-ling, 1988). Kennedy and Murray (1991), using a lexical decision task, found that flicker resulted in saccadic irregularities. At low refresh rates, subjects misjudge the extent of target displacements that take place during saccades, in the direction of a breakdown in space constancy (Macknik, Fisher, & Bridgeman, 1991). A serious and largely unrecognized danger is misinterpretation and limited control over stimulus duration at the millisecond time scale.

All VDTs are illuminated by a spot moving rapidly across the screen in a raster pattern, covering the surface 60 to 120 times per second. Visual persistence makes screen illumination appear continuous, because the raster rates exceed the critical flicker fusion rate. Scanning begins with a single horizontal row of pixels illuminated successively across the screen. Just after the end of the scan, a horizontal synchronization pulse triggers another scan, slightly lower on the screen. At the end of the final scan, a vertical synch pulse restarts the raster at the beginning.

Early VDTs were strobed at 60 Hz, but as large screens with bright backgrounds were introduced, flicker in peripheral vision became noticeable. For this reason, faster strobe rates were introduced—66 Hz in Sony Trinitron tubes, then in several tubes at refresh rates of 75 Hz, 100 Hz, and 120 Hz. All of these rates are in use today. The motivation for faster rates was solely to avoid visible flicker; the industrial standard for VDTs states only that flicker should not be visible for 90% of users.

DISPLAY DURATIONS

In most psychophysical experiments, small regions of the screen are illuminated briefly. A small region is strobed in only a few horizontal sweeps of the raster, requiring only a few microseconds per sweep. In a 1,000-line high-resolution display strobed at 100 Hz, for example, a row of alphanumeric characters at a standard height of 10 pixels requires $1/100 \times 10/1{,}000$ s, or 100 µs. This is practically instantaneous compared with the temporal bandwidth of human vision. Displays of larger vertical extent require proportionately more time for complete display. Visual stimulation at any given point of the retina, however, normally comes from a single pixel that is strobed in less than a microsecond. The stimulus duration is then given by the persistence of the monitor's phosphor, the dwell time of the flying spot on that pixel being negligible. A given pixel is dark most of the time. Independent of other optical characteristics of a display, the resulting delay in stimulating each retinal location leads to a quantitatively predictable slowing of reading speed on VDTs (Montegut, Bridgeman, & Sykes, 1997).

Most researchers assume that the duration of a stimulus during a single scan equals the reciprocal of the raster rate in hertz. For a 60-Hz raster, the duration is 16.67 ms; for a 66.67-Hz raster, it is 15 ms, and so on. To convert from raster rate to duration by this algorithm, one simply calculates

$$\frac{n}{f} = \text{duration}, \tag{1}$$

where n is the number of scans and f is the raster frequency.

This algorithm is incorrect, however: Because stimulation is intermittent, the total duration of stimulation at any given pixel, from the first brightening of the pixel to the last visible persistence of the phosphor, is

$$\frac{n-1}{f} + p = \text{duration}, \tag{2}$$

where p is the phosphor persistence and the other terms are defined as in Equation 1. The stimulus does not continue for the entire duration of the last raster sweep, but ends as soon as the phosphor brightness decays. This duration p varies with color and type of phosphor, but for typical color screens it is about 4 ms. Phosphors in oscilloscope displays can be even shorter: The green P31 phosphor, with a medium-short persistence, decays exponentially to 1% of peak brightness in 0.02 to 2 ms (Keller, 1983). Visible phosphor persistence can be longer if an observer is dark-adapted, but in most psychophysical experiments, a pixel is strobed repeatedly, preventing dark adaptation.

For the example of 4 raster scans, at a frequency of 67 Hz and a persistence p of 4 ms, Equation 1 gives a duration of 60 ms (see Fig. 1). But the actual duration from Equation 2 is 49 ms. In general, calculations from Equation 1 will be 11 ms too long. This is not a serious error for long-duration stimuli, but for a display of only a few raster scans, the percentage of error can be substantial. For a single scan, Equation 1 overestimates stimulus duration by more than 300%. Whatever the decay function of visual persistence, that decay will begin 11 ms sooner than this algorithm estimates.

Overestimations of duration are particularly troublesome when comparing tachistoscope and VDT experiments. Equation 1 will make interstimulus intervals seem shorter than they are because the first stimulus becomes invisible at a time when the algorithm indicates that it is still present. This discrepancy between real and calculated duration is critical for masking and priming experiments. And Equation 2 measures only duration from first light to last light, neglecting the dark

Address correspondence to Bruce Bridgeman, Department of Psychology, University of California, Santa Cruz, CA 95064; e-mail: bruceb@cats.ucsc.edu.

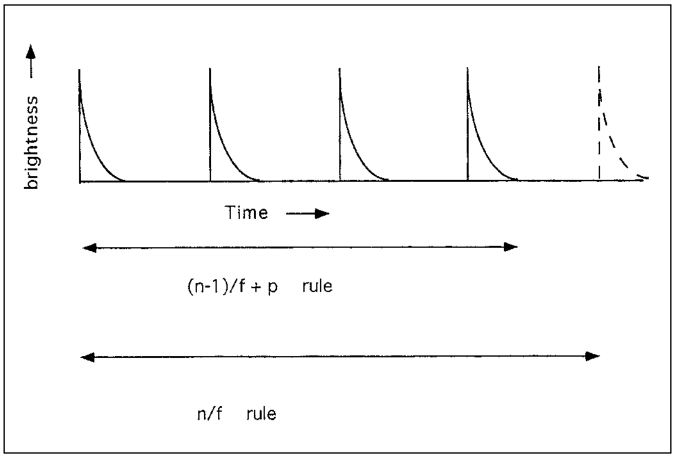

Fig. 1. Stimulus duration at a given location on a raster-scanned video display terminal, as estimated by two algorithms. The top line displays brightness profiles for a pixel undergoing four raster scans in a 66.67-Hz display: a refresh every 15 ms (vertical lines) followed by an exponential decay lasting about 4 ms. The commonly used n/f rule overestimates the time during which a stimulus is available on the retina by including the blank poststimulus interval preceding the next (undisplayed) scan, shown in dashed lines. Total duration by the n/f rule is 60 ms, whereas duration by the $(n - 1)/f + p$ rule is 49 ms.

intervals between screen refreshes. Also neglected are phase delays between the top and bottom of the display, which can reach up to 16 ms for both onset and offset (I thank a referee for pointing this out).

SURVEY OF FREQUENCY OF USE

From Equation 2, the correct duration calculation seems obvious. In common usage, however, authors almost always use the n/f algorithm (Equation 1), and therefore overestimate the duration of what their subjects saw.

I surveyed issues of *Psychological Science* for the first quarter of 1997, looking for articles reporting use of VDT displays and specifying stimulus durations. I took as evidence for use of the n/f algorithm a set of durations that were exact multiples of one another (difficult to achieve under Equation 2) and that were multiples of a raster duration at one of the commonly used raster frequencies.

Six articles met the methodological and descriptive criteria. Of these, all used the n/f algorithm instead of specifying the true duration of the stimuli as in Equation 2.

DISCUSSION

Overestimation of stimulus duration is widespread in psychophysics; a survey of the 1997 program abstracts of the Association for Research in Vision and Ophthalmology revealed more than a dozen similar errors, and only one study that got it right. Workers in the field of motion often escape this error by specifying the number of frames of motion rather than duration.

Interpreting duration in black-on-white displays is more difficult, for brightness in a black target area never changes during display. If the stimulus is defined by simultaneous contrast with the background, however, the arguments in this Commentary would apply.

Equation 1 can lead to almost comical misestimates of stimulus duration. For a single raster scan, for example, stimulus duration by Equation 2 is just p, the phosphor persistence, because $n - 1 = 0$ and the first term of the expression drops out. Thus, stimulus duration is independent of raster rate. But by Equation 1, duration depends on raster rate and is independent of phosphor persistence. Thus, a single sweep at 60 Hz gives an apparent duration of 16.67 ms, whereas the same sweep at 120 Hz gives 8.33 ms. Apparent stimulus duration can be halved without any physical change on the screen except for the few microseconds less time required to strobe the stimulus area. This is reason enough to switch to Equation 2. Editors and referees should be especially mindful of this problem.

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