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Effect of varying CRT refresh rate on the measurement of temporal summation.

Pádraig J. Mulholland[1,2], Margarita B. Zlatkova[2], Tony Redmond[3], David F. Garway-Heath[1], Roger S. Anderson[1,2]

[1] National Institute for Health Research (NIHR) Biomedical Research Centre at Moorfields Eye Hospital NHS Foundation Trust and UCL Institute of Ophthalmology, London, United Kingdom.
[2] Vision Science Research group, University of Ulster, Coleraine, Northern Ireland, United Kingdom.
[3] School of Optometry and Vision Sciences, Cardiff University, Cardiff, United Kingdom.

CORRESPONDING AUTHOR: Pádraig J. Mulholland, Moorfields Eye Hospital, 162 City Road, London, EC1V 2PD, United Kingdom.
Email: Padraig.Mulholland@moorfields.nhs.uk **Tel.**: +44(0)20 7566 2835

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Abstract

Purpose: To quantify the effect of cathode-tube-ray (CRT) monitor refresh rate on the measurement of the upper limit of complete temporal summation (critical duration) in the peripheral visual field of healthy observers.

Methods: Contrast thresholds were measured for seven achromatic spot stimuli (diameter 0.48º) of varying duration (nominal values: 10-200 msec) at an eccentricity of 8.8º along the 45°, 135°, 225° and 315° meridians of the visual field in three healthy, psychophysically experienced observers. Stimuli were presented on a CRT display with a refresh rate of 60 and 160 Hz. Contrast thresholds were expressed as contrast energy with stimulus durations being estimated using (i) the sum-of-frames (SOF) method and (ii) Bridgeman's method incorporating measurements of phosphor persistence. Estimates of the critical duration were produced using iterative two-phase regression analysis.

Results: With stimulus duration expressed as SOF equivalent the critical duration was, on average, 10.6 msec longer with a refresh rate of 60 Hz (mean 45.7 msec, SD 10.1 msec) relative to 160 Hz (35.1 msec, SD 7.6 msec). When the Bridgeman method was used, minimal differences (1.8 msec) in critical duration values between the two refresh rates (60 Hz: 33.0 msec, SD 9.4 msec; 160 Hz: 31.2 msec, SD 7.0 msec) were observed. Identical trends were observed in all three subjects.

Conclusion: Psychophysical measurements of temporal summation are independent of variations in CRT refresh rate when the Bridgeman method, incorporating measured values of phosphor persistence, is used to estimate stimulus duration. This has significant implications for the specification of stimulus duration in psychophysical studies of vision employing conventional display monitors.

Introduction

The value of any visual psychophysical investigation is highly dependent upon the precise control of stimulus presentation parameters. Within the published literature, cathode ray tube (CRT) monitors remain in widespread use for the presentation of psychophysical stimuli despite their lack of production.[1, 2] Image generation in this class of monitor occurs as a result of the activation of individual phosphor particles on the posterior surface of the display screen by an incoming electron beam. Once activated, each phosphor displays a rapid increase in luminance output followed by an exponential decline in activity until energy emission ceases. Owing to this decay, the re-excitation or *refresh* of each phosphor is required for the desired image to remain on the display screen. The number of occasions each pixel is re-activated in one second determines the refresh rate, with the frame duration being calculated as the reciprocal of this value. Because of the sequential re-activation of each pixel, the temporal delivery of light energy to the eye from a CRT is intermittent with the rate of flicker being dependent on the refresh rate selected (*figure 1*). Despite such periodic temporal output, flicker is not perceived as long as the refresh rate is kept above the critical flicker frequency (CFF). Currently, the majority of studies using a CRT employ refresh rates of 60 Hz (range: 60-200 Hz).[2]

Although widely used, CRTs and other frame based display monitors (e.g. organic light emitting diodes) are not ideal for the psychophysical examination of vision. Their primary limitation relates to temporal display artifacts resulting from the image generation process.[1-4] Specifically, CRT monitors are unable to properly replicate stimuli with square wave temporal profiles due to phosphor decay and reactivation.[1, 2] This limitation introduces two specific issues for the use of CRT monitors in vision science – (1) the generation of neural artifacts that can potentially influence the results of any psychophysical experiment and (2) difficulties in meaningfully specifying the duration of stimuli.

Within the literature, the potential for neural artifacts arising from the pulsed nature of CRT output has been widely discussed.[3] Gawne and Woods,[5] in a neurophysiology study, report that pulsed stimuli with a gradual offset, such as those generated on a CRT, do not produce responses in neurons within cortical area V1 that are comparable to those gained when using a true square wave stimulus of equal nominal duration. Zele and Vingrys[6] also propose neural artifacts to occur at the level of the retina due to the formation of high-frequency noise, this effect being amplified when lower refresh rates are used. Shady et al.[7] in a psychophysical study reported that adaptation to flicker could affect visual thresholds even if the flicker frequency is above the CFF. They point out that, even if flicker is not perceived, low CRT refresh rates can influence visual sensitivity, advising that high refresh rates should be used where possible to avoid artifactual deficits in visual sensitivity. Despite evidence that variations in refresh rate can influence some neural processing in the visual pathway,[5, 6] it is unknown if such changes can also influence the integration of light photons over time (temporal summation), and specifically the critical duration (figure 2).

The inability of a CRT to reproduce stimuli with a square wave temporal profile also creates problems when attempting to specify the duration of psychophysical stimuli. Square wave stimuli generated on a CRT characteristically have a rapid onset, a variable temporal profile and display a tapered offset due to phosphor decay in the final frame of presentation (*figure 1*). The most commonly used method to estimate presentation duration is the sum-of-frames (SOF) calculation. This method calculates presentation duration on the basis that stimuli may only be integers of frames when generated on a CRT display and assumes contiguous light output over the duration of the stimulus with no allowance being made for phosphor activation and decay within each frame.[2, 3] The SOF method, although convenient, can lead to significant over-estimation of stimulus duration, this being amplified for single frame presentations where the period of phosphor activation is shorter than the frame duration (*figure 3a*). In response to such limitations, Bridgeman[1] proposed that stimulus duration be measured from the point of phosphor activation in the first frame to the temporal limit of phosphor activity in the final frame of presentation. Although theoretically superior to the SOF method, knowledge of the phosphor decay time is required, it also being unknown if this value is affected by luminance output. Furthermore, as the SOF method is used almost exclusively in the literature to specify stimulus duration on display monitors[2] it is currently unknown what effect, if any, using the Bridgeman method will have on the results of a psychophysical study of temporal vision.

In this study, we sought to investigate the effect of varying refresh rate on measurements of temporal summation for an achromatic spot stimulus, generated on a CRT display under photopic conditions. The purpose of this investigation was two-fold. Primarily we wished to determine if the selection of a low (60 Hz) or a high refresh rate (160 Hz), in those studies employing frame based display monitors, impacts upon the measurement of temporal summation in healthy observers. We also wanted to determine the effect of specifying stimulus duration using the SOF and Bridgeman methods on the perceived trends within a psychophysical study of temporal vision.

Methods

Subjects

Three healthy volunteers, aged 25, 31 and 48 years with normal or corrected–to-normal vision, were included in this study. These included two of the authors (PJM and RSA) and one naive observer (NCS). Corrected Snellen visual acuity was 6/5 (20/17) with a refractive error within ±3 diopters (D) and 0.50 D astigmatism in all subjects. Each subject's right eye was examined with a natural pupil (5-7mm diameter). Ethical approval was gained from the London-Central National Research Ethics Service committee and the research protocol adhered to the tenets of the Declaration of Helsinki.

Apparatus & stimuli

Stimuli were presented on a γ-corrected 21" Phillips FIMI MGD-403 achromatic monitor (Ampronix, Irvine, CA, USA) with a pixel resolution of 500 x 720. Two refresh rates of 60 Hz and 160 Hz were used. A ViSaGe MKII Visual Stimulus Generator (ViSaGe, Cambridge Research Systems, Rochester, UK) and Cambridge Research Systems toolbox (v.1.27) for MATLAB (version R2011a, The MathWorks, Inc., Natick, MA, USA) were used to generate stimuli. Chromaticity co-ordinates of stimuli, background and central fixation cross were $x = 0.258$ and $y = 0.257$ as measured using a colorimeter (ColorCal MKII, Cambridge Research Systems, Rochester, UK). For all trials, circular stimuli of diameter 0.48° (equivalent to a Goldmann size III clinical perimetric stimulus) were presented on a background of 10 cd/m^2. The CRT display was viewed from a distance of 60 cm with subjects placing their head in a chin-rest during examinations. All subjects were optically corrected for the test distance using full aperture trial lenses.

The temporal profile of luminance output from the CRT display, in addition to the refresh rate of the display, was measured using an Optical Transient Recorder 3

(OTR-3, Display Metrology & Systems GmbH & Co. KG, Germany) configured for unipolar output. To permit full measurement across the complete range of possible contrast levels, a gain or amplitude setting of S3 and variable voltage range between 1 and 10V were employed, together with a receiver aperture of 3 mm. Prior to any data collection measurements were performed in the absence of light (five measurements of 1 second duration) to account for any noise within the OTR-3 device. All other OTR-3 recordings were normalized using the mean amplitude value in dark conditions as a baseline, any excursion beyond this point representing light output.

Measurement of phosphor activity

Circular spot stimuli of diameter 42 mm and single frame duration were presented at one of the test locations (8.8° eccentricity along 45° meridian). The OTR-3 was positioned so that the center of the receiver aperture was perpendicular to, and coincidental with, the center of the test stimulus. Measurements were repeated for all contrast levels in an otherwise dark room.

Estimated stimulus contrast energy

To estimate contrast energy (ΔE) from luminance values, we assumed the CRT luminance output to be a square wave, with equation 1 then used to estimate ΔE for stimuli of varying duration. The value *L* corresponds to the luminance measurement collected by the ColorCal II, L_b the background luminance, *f* the stimulus duration (expressed as number of frames) and *r* the refresh rate.

$$\Delta \mathrm{E} = \left(\frac{\square}{\square}\right)(L - L_b) \tag{1}$$

Calculation of stimulus duration

Stimulus duration was calculated using both the SOF (t_{sof}) and Bridgeman methods (t_{bn}). Equation 2 was used to calculate SOF durations in msec where *f* is the number of frames within the stimulus and *r* the refresh rate.

$$\square_{\square\square\square} = \square\left(\frac{1000}{\square}\right) \tag{2}$$

Stimulus duration was also estimated from the point of phosphor activation in the first frame to the temporal limit of activity in the final frame of presentation (Bridgeman method, eq. 3).

$$\square_{\square\square} = \left[(\square - 1)\left(\frac{1000}{\square}\right)\right] + \square \tag{3}$$

Bridgeman[1] suggests that a constant value for phosphor persistence (*p*), or decay time, be incorporated in the calculation. Unfortunately the percentage decay to which *p* should be measured (i.e., temporal limit of phosphor activity), together with the point above zero output that defines the start of phosphor activity, was not specified. For the purposes of this study we specified both the start and end of phosphor activity within a frame to be 10% above baseline (figure 3a). When plotted as a function of luminance output (fig. 3b) and energy values (fig. 3c, see appendix for calculation of output energy from OTR-3 measurements), no change in *p* was observed (60 Hz: $r^2 = 0.11$; 160 Hz: $r^2 = 0.10$, both $P>0.05$ for r^2 values). In view of this *p* was calculated as the mean of all measurements collected (1.8 msec).

Psychophysical procedure

Two subjects (RSA and NCS) underwent one complete examination for each refresh rate. The experiment was performed twice at each refresh rate (in a random order) for subject PJM. In each experiment, contrast thresholds were measured for achromatic spots (0.48°) of varying nominal duration (10-200 msec) at 8.8° eccentricity in the visual field along the 45°, 135°, 225° and 315° meridians, in an interleaved fashion. A yes/no response paradigm was employed with a 1/1 staircase that terminated after six reversals. Threshold luminance was calculated as the mean of the final four reversal values at each test location. Subjects were instructed to fixate a central cross target and press a response button if a stimulus was seen. Reliability was assessed with blank presentations (false positive catch trials) that accounted for approximately 30% of all presentations. The session was halted and repeated if the false positive rate exceeded 20%. Prior to data collection, subjects were given one or more practice sessions, until it was clear that they fully understood the task.

Data analysis

Temporal summation functions were generated with stimulus durations calculated as SOF (eq. 3) and modified Bridgeman equivalents (eq. 4). Each summation function, expressed as log ΔE vs. log stimulus duration, was constructed for each subject using thresholds (mean across all test locations and test runs) for stimuli of different durations. Two-phase regression analysis[8] was used to estimate the critical duration from the temporal summation curves. As part of this analysis, the slope of the first line was constrained to 0 in accordance with Bloch's law (complete temporal summation). The slope and intercept of the second line, along with the point at which the two component lines met (breakpoint), were free to vary. The critical duration was estimated, following multiple iterations (maximum 1000), as the breakpoint in the function.

Results

When stimulus duration was expressed as SOF, equivalent critical duration values were greater for stimuli presented with the lower refresh rate of 60 Hz (mean 45.7 ± 10.1 msec) compared with 160 Hz (mean 35.1 ± 7.6 msec). This trend was seen for all subjects with a mean difference of 10.6 ± 2.8 msec (*figure 4*, upper panel). This difference was statistically significant when examined with a paired t-test (P=0.02). When the Bridgeman method was used to estimate stimulus duration, minimal differences (mean 1.8 ± 2.8 msec) in critical duration were observed with refresh rate (*figure 4*, lower panel). These differences were not statistically significant (P=0.43 in a paired t-test). Mean critical duration values for the 60 Hz and 160 Hz frame rates were 33.0 ± 9.4 msec and 31.2 ± 7.0 msec, respectively. Unsurprisingly, the critical duration values were shorter when stimulus duration was expressed using the modified Bridgeman method compared to the SOF method. If the data collected using the 60 Hz display are considered, critical duration values are on average 12.7 msec shorter using the modified Bridgeman durations compared to the SOF equivalent. For the same method of threshold expression, the discrepancy was much smaller (3.9 msec) for the 160 Hz data set.

The discrepancy in stimulus durations when expressed as SOF and modified Bridgeman equivalents (mean values across all locations and subjects in study) for each nominal stimulus duration (i.e. those specified in experimental code) may be seen more clearly in *figure 5*. The SOF method consistently yields higher estimates of stimulus duration across the range of stimuli presented in this study. This discrepancy is greatest for the lower refresh rate of 60 Hz. It may also be seen that for stimuli of single frame duration the SOF method can introduce particularly large errors, these inaccuracies being greatest for displays running with a low refresh rate.

Discussion

Temporal summation with variations in refresh rate

The present study shows that the critical duration of temporal summation for a perceptually single achromatic spot stimulus is independent of CRT refresh rate when the Bridgeman method, incorporating measured values of phosphor persistence, is used to estimate stimulus duration. Although no previous experiment has investigated the temporal summation of a CRT signal, a variety of studies have explored the summation of pairs of incremental stimuli presented with varying temporal separations. A finding common to these studies is the complete summation of energy for temporally double-pulsed spot stimuli when presented with short inter-stimulus intervals up to a critical duration.[9-12] After this partial summation is observed until a point is reached at a separation of approximately 60 msec where cancellation or inhibition is seen to occur.[11, 12] Such trends have been attributed to the presence of bi-phasic temporal filters in the visual system.[11]

If the response to the temporally modulated stimulus at threshold is considered to be mediated by a linear filter (see Watson[13] for a review), it can be shown that the visual thresholds within the critical duration should not change with the refresh rate of the monitor. It has been proposed that the response of the visual system will be constant if the product of the amplitude spectra of the stimulus and amplitude response of the linear filter is equal within the critical duration.[13] Assuming that the amplitude response remains constant within each subject under the conditions of this experiment (i.e. identical background luminance, stimuli, etc.), it can be seen from the amplitude spectra (*figure 6,* lower panel*)* that the peak amplitude (1st harmonic) is identical for the 60 Hz and 160 Hz stimuli. Treating the visual system as a linear filter with a certain amplitude response with a maximum at 7-8 Hz and a cut off frequency at about 40 Hz,[14] it can be seen that increasing the refresh rate of the display should not significantly influence the product (convolution) of the amplitude spectra of the stimulus and the amplitude response of the linear filter in the range of maximal response, with the result that visual thresholds and thus the critical duration will remain invariant of refresh rate.

One study has, however, challenged the notion that the visual system may completely sum stimuli presented on a CRT display with a low refresh rate. Using a large stimulus diameter (17°) and high retinal illuminance (700 trolands), Rashbass[12] found summation to be incomplete when the time interval between two successive incremental pulses was 8 msec, this being noticeably shorter than the critical duration (16 msec) found under identical test conditions for a single stimulus of equal total duration and area. One possible explanation for the discrepancy between the work of Rashbass[12] and the results of this study is the experimental conditions used. The temporal summation of single stimuli is known to be influenced by a number of factors including stimulus area[15, 16] and background adapting luminance,[17] with a shorter critical duration at higher adapting illuminance and larger stimulus size. In a similar fashion, the summation of stimuli composed of multiple incremental pulses is affected by factors relating to both the stimulus and environment.[11, 13] It is thus likely that the relatively smaller stimulus (0.48°) and lower background luminance (10 cd/m^2) used in this investigation would lead to a longer critical duration in a temporal double-pulse experiment and, as a result, no difference in the critical duration with refresh rate.

Specifying stimulus duration

The inherent difficulty in estimating the duration of a stimulus presented on any display monitor has been widely reported in published literature.[1-3, 18] In agreement with previous work, the SOF method, as applied in this study, appears to overestimate durations for stimuli with a small number of constituent frames.[1, 4, 18] Significantly, these disparities appear to be greater when the lower refresh rate of 60 Hz was selected (*figure 5*). Considering the example of a nominal 10 msec stimulus reproduced on a display with a 60 Hz refresh rate, the SOF estimation of duration (1 frame, 16.7 msec) is 828% greater than the Bridgeman equivalent (1.8 msec) for the group of subjects in this study. For the same stimulus generated on a display running at 160 Hz (2 frames, t_{sof} = 12.5 msec, t_{bn} = 8.1 msec), the discrepancy is smaller (56%). These differences and their relative effect on psychophysical thresholds are, however, partly dependent upon the type of phosphor used. Di Lollo et al.[19] found the persistence of the P31 phosphor to be visible several hundred milliseconds after presumed stimulus offset in dark-adapted conditions and also in the presence of a 'veiling glare' (achieved with two lamps with an output attenuated to 0.33 cd/m^2). This effect was amplified for displays using phosphors of high persistence and stimuli of high luminance.

A number of authors have questioned the value in accurately specifying the duration of stimuli when shorter than the critical duration.[18] It is well established that spatial and temporal resolution decrease with increasing levels of summation,[20] thus if a stimulus is shorter than the critical duration, the visual system will only differentiate on the basis of luminous flux and not duration. The results of this study present a strong argument against this view. When examining the temporal aspects of vision, such as summation, it is clear that small discrepancies in stated duration can induce large deviations from the true trends in a given data set. Elze [4] in an examination of simulated frequency-of-seeing data found the maximum likelihood method used to generate each psychometric function to be influenced by the method used to estimate stimulus duration. This difference was attributed to lack of assumed proportionality of the SOF method compared with the Bridgeman calculation. More simply, a stimulus composed of two frames is assumed by the SOF to be double the duration of a single frame presentation. This is not the case when duration is specified as a Bridgeman equivalent. In a similar fashion the results of the iterative two-phase regression analysis used to estimate the critical duration in this study was also influenced by the method chosen to estimate stimulus duration.

In this study, Bridgeman's method was exclusively applied to estimate the duration of stimuli generated on a CRT display. The use of this calculation may, however, be also extended to describing the duration of stimuli produced on other display types such as organic light-emitting diode (OLED) monitors whose pulsed output resembles that of a CRT.[21] Although the temporal output of OLED monitors varies from that of a CRT (i.e. a more rapid decay to 0% of peak output within a frame) there appears to be a period within each frame where no energy output takes place. Ito et al.[21] demonstrated that a stimulus alternating in RGB values from (255, 255, 255) to (192, 192, 192) with each frame refresh on a Sony PVM-2541 OLED monitor (refresh rate 60 Hz) led to periods of light emission (~7.5 msec) followed by intervals (~6.8 msec) where no light output was detected. Considering this evidence it is also likely that very short duration stimuli produced on OLED displays might also suffer from over-estimations of stimulus duration should the SOF method be used. In this situation the Bridgeman method incorporating persistence (p) values equal to the period of light emission in a single frame could be applied to improve the accuracy of any estimates of stimulus duration.

Refresh rate selection

The issue of temporal presentation artifacts associated with display monitors, together with methods for their reduction, has been widely discussed within the psychophysical literature. Specifically, temporal variations in luminance output secondary to phosphor decay in CRT displays have been highlighted as a drawback when attempting to accurately estimate the duration of stimuli presented and also replicate stimuli with square wave temporal profiles.[1-3] To partially alleviate such issues, it has been suggested that a high refresh rate should be employed. This assertion appears to have been made without regard to how the visual system sums the temporal output from a CRT display or whether varying refresh rate impacts upon psychophysical thresholds. It is clear from the results of this study that the upper limit of complete temporal summation remains constant *in contrast energy terms* despite variations in the nature of energy delivery resulting from changes to refresh rate. Despite potentially influencing the activity of retinal ganglion cells[6] and cortical neurons in area V1,[7] low refresh rates do not appear to impact upon the investigation of temporal vision provided output from the CRT display is accurately characterised in terms of both energy and duration using appropriate metrics.

A wide range of CRT refresh rates have been selected for use in both the clinical and basic psychophysical examination of vision, in order to reduce neural artifacts,[6, 22] improve temporal resolution,[3] reduce flicker perception at high background luminance[1] and also reduce the effects of adaptation to invisible flicker on visual sensitivity.[7] In this study, we have demonstrated that the selection of refresh rate may also have an effect on the ability to accurately specify stimulus duration, thus leading to secondary and, most importantly, artificial variations when investigating temporal visual processing. Interestingly, the difference between critical duration values estimated using SOF stimulus durations, compared with the more accurate Bridgeman durations, was smallest when a high refresh rate was used. This finding may be due to an improved correspondence between the temporal profile of a stimulus produced with a high refresh rate and the contiguous energy output assumed by the SOF method of classifying stimulus duration on a CRT display. As the measurement of energy output, or indeed phosphor decay time, may not be practicable in all situations, it is strongly advisable that, when using the SOF method, a high refresh rate be used where possible to reduce any disparities between the *real* and estimated stimulus durations.

Conclusions

CRT displays continue to offer psychophysicists the ability to present a wide variety of accurately calibrated visual stimuli. The capability of the visual system to sum energy delivered over a given temporal window appears to be independent of duty cycle changes, secondary to variations in refresh rate, for an achromatic stimulus of 0.48° diameter. It is clear from the results of this study that the quantification of CRT output, specifically presentation duration, can greatly impact upon the investigation of temporal vision using this class of display monitor. The use of accurate metrics that make reference to the *real* temporal profile of monitor output partially alleviate such issues and have the potential to serve as universal metrics through which data collected using varying CRT refresh rates, or indeed of different monitor types, may be accurately, and more importantly, validly compared.

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Figures

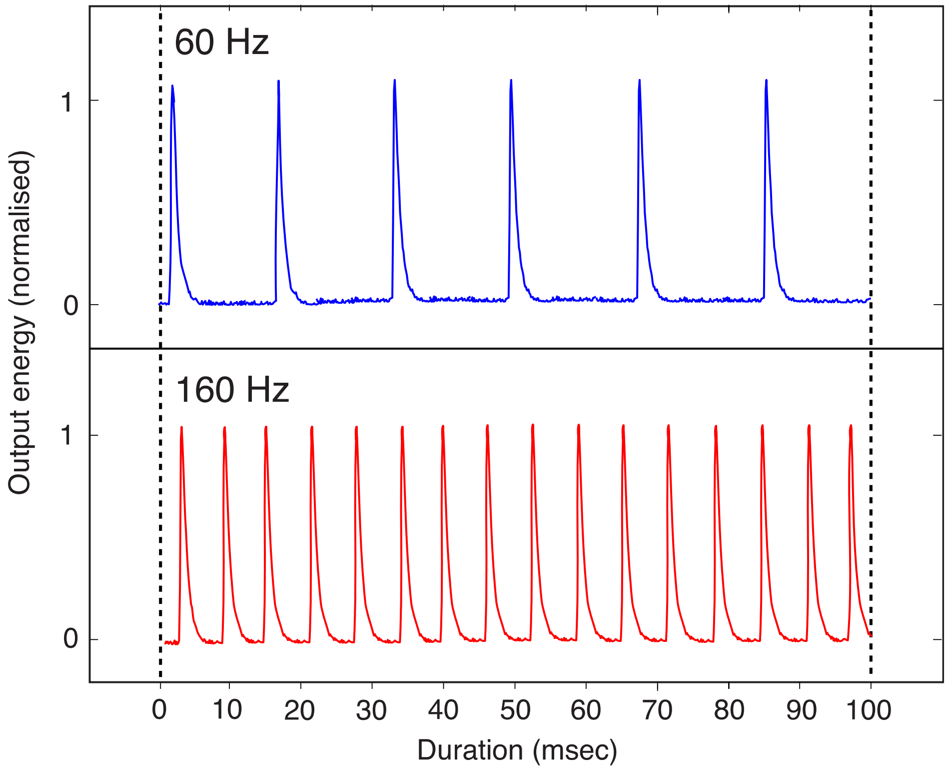

Figure 1: Comparison of the temporal profile of luminance output for a 100 msec stimulus as measured on a CRT display running at 60 Hz (upper panel) and 160 Hz (lower panel).

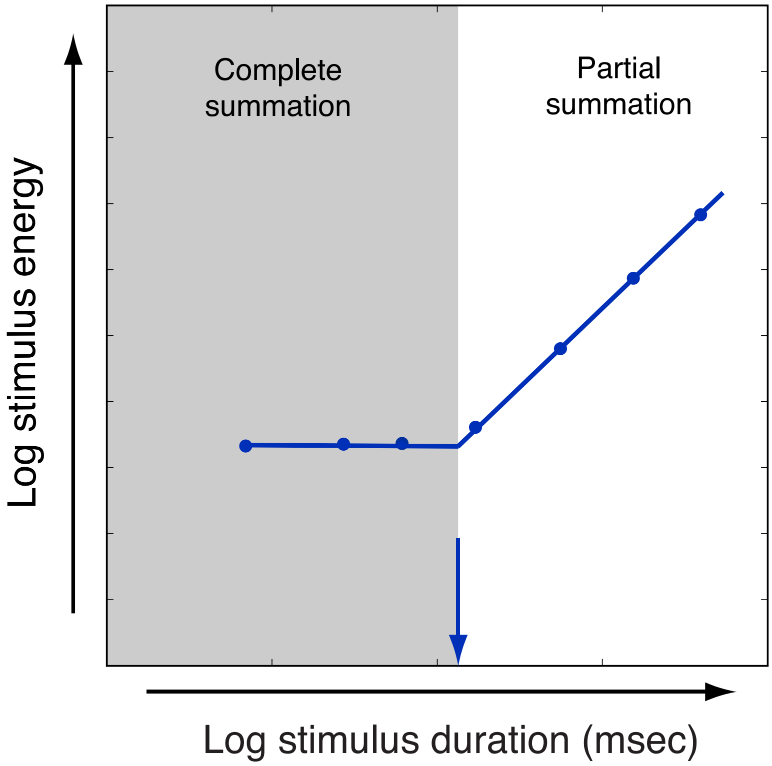

Figure 2: Schematic temporal summation function. For short duration stimuli there is complete summation (grey shaded area) and the data may be fit with a line of slope zero for calculated energy data up to the critical duration (blue arrow). Beyond the critical duration incomplete summation is exhibited

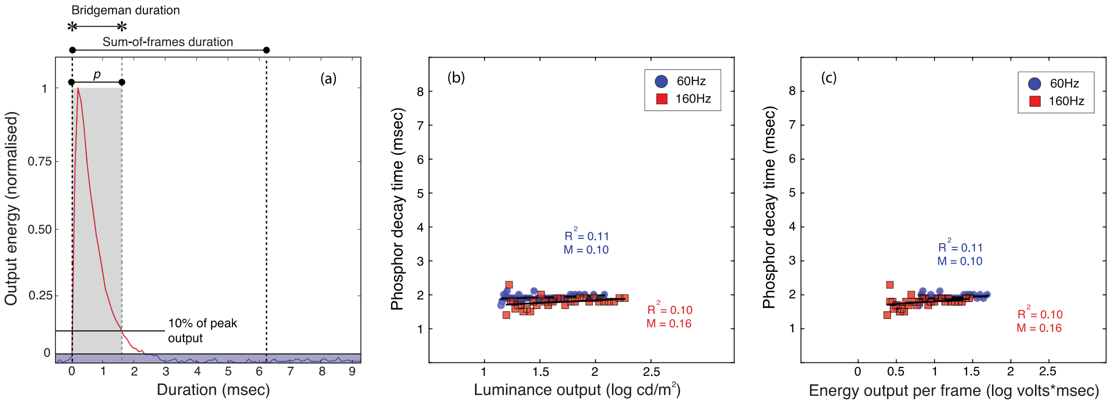

Figure 3: (a) Schematic detailing how phosphor persistence/decay time (*p*) was calculated from phosphor activity plots. Dashed lines indicate the start of the frame, decay time and end of frame (refresh 160 Hz). Stimulus duration as specified using the SOF and modified Bridgeman methods are also listed for reference. (b-c) Phosphor decay times measured for the P45 phosphor at a range of (b) luminance and (c) energy output levels (E_{stim} for single frame presentation of one pixel area) for a CRT running at 60 (blue circles) and 160 Hz (red squares).

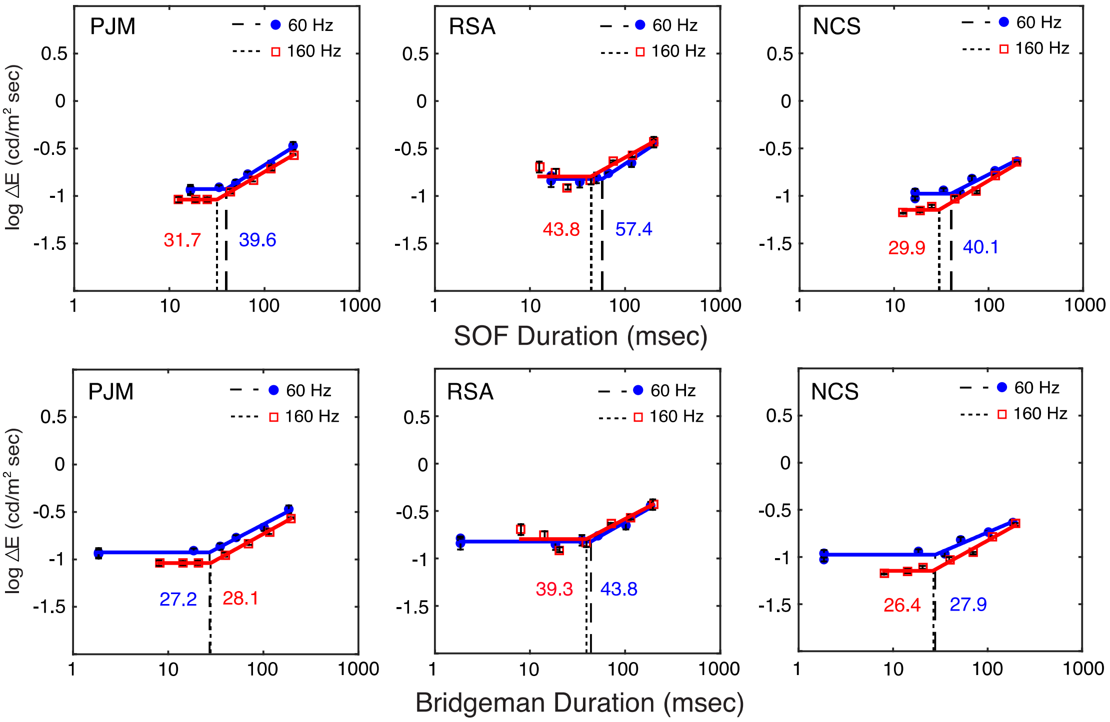

Figure 4: Temporal summation functions for threshold data expressed as contrast energy values for individual subjects and stimulus durations specified as SOF equivalent (upper panel) and Bridgeman values (lower panel). Error bars included represent the standard error of the mean (SEM). The breakpoint in each function (dashed line) indicates the critical duration.

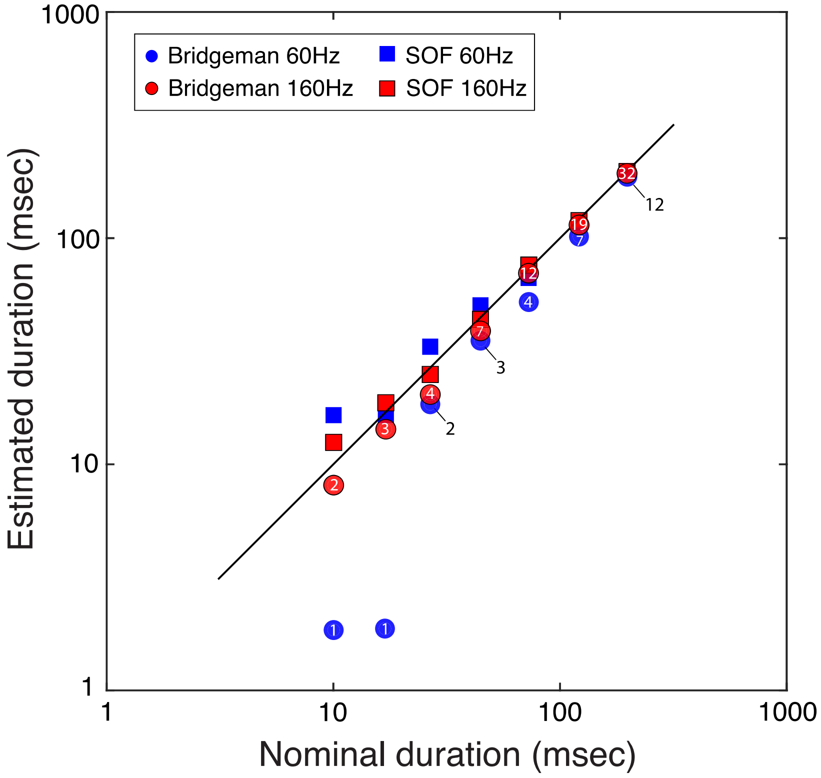

Figure 5: Comparison of stimulus duration as estimated using the SOF (squares) and Bridgeman methods (circles) for stimuli generated on display with 60 (blue) and 160 Hz frame rates (red). Nominal stimulus durations represent the duration specified in the experimental code. The number of constituent frames in each stimulus is included as a label on the Bridgeman data points.

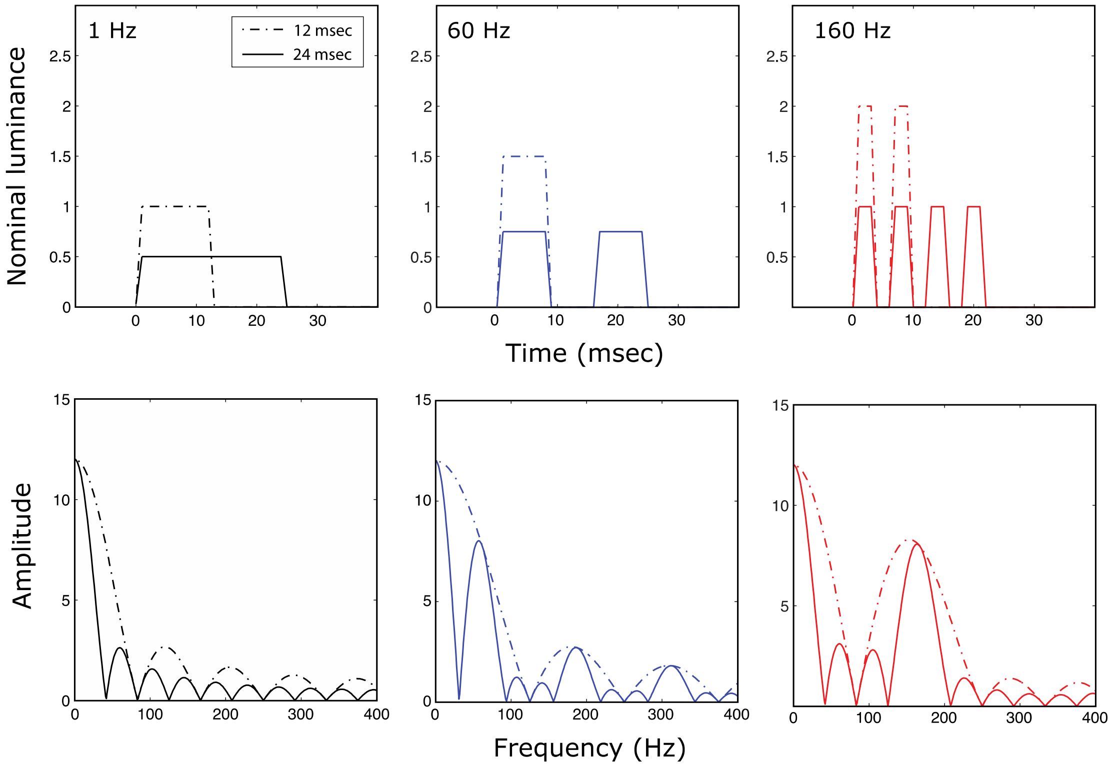

Figure 6: Schematic temporal profile (upper panel) of threshold stimuli of duration shorter than the critical duration (12 & 24 msec, equal total energy) generated with temporal frequencies of 1Hz (leftmost plot, black lines), 60 Hz (center plot, blue lines) and 160 Hz (rightmost plot, red lines) along with corresponding amplitude spectra (lower panel). The 1 Hz frequency is included for illustration only as reference to a true square wave stimulus.

Appendix

Estimating stimulus energy from measurements of stimulus temporal profile

To estimate the actual contrast energy based on the *true* temporal profile of the stimulus, measurements were performed using the OTR-3. The raw output data for each OTR-3 measurement was initially plotted with MATLAB. The 'stimulus ON' region (labeled 'Stimulus' in fig. A1a) was subsequently delineated manually to remove much of the phosphor activity attributed to background luminance. Phosphor activity was then charted in detail (fig. A1b). Using this plot, the point at which phosphor activation begins (fig. A1b, black dashed line), in addition to point at which activity decays to 0% of maximum (fig. A1b, red dashed line), was manually selected using a graticule. In doing this an accurate plot of phosphor activity, from first activation to final decay, is produced (fig. S1b, black dashed line – red dashed line). To estimate the total energy output over this period the area under the curve (AUC) for each phosphor activity plot was calculated using the composite trapezoid rule. This process was performed for all five OTR-3 measurements at each contrast level. The energy output from each pixel within the period of phosphor activity (E_P) was subsequently calculated by dividing the mean AUC value by the estimated number of pixels covered by the aperture of the OTR-3 receiver (31 pixels).

The energy output for a single pixel over the duration of a whole frame (E_F) was also calculated. This was performed in an identical manner to that described for E_P with the exception that the AUC calculation for phosphor activity was made over a whole frame rather than just the phosphor decay time (fig. A1b, black dashed line – green dashed line). Once E_F and E_P were calculated for a single phosphor activation at each contrast level the total energy output for a given spot stimulus presentation (E_{stim}) may be estimated using equation A:

$$E_{stim} = \{[(f - 1)\,E_F] + E_P\}\,n \qquad \text{(A)}$$

where *f* is the number of constituent frames within a stimulus presentation and *n* the number of pixels over the area of the stimulus. This method, like the modified SOF model proposed by Bridgeman,[1] accounts for phosphor decay by calculating energy output from the start of the first frame to the temporal limit of phosphor activity in the final frame of stimulus presentation. In the case of this study output energy (E_{stim}) was calculated for a single pixel presentation of one frame duration. These values were then plotted as a function of phosphor decay time in *figure 3c*.

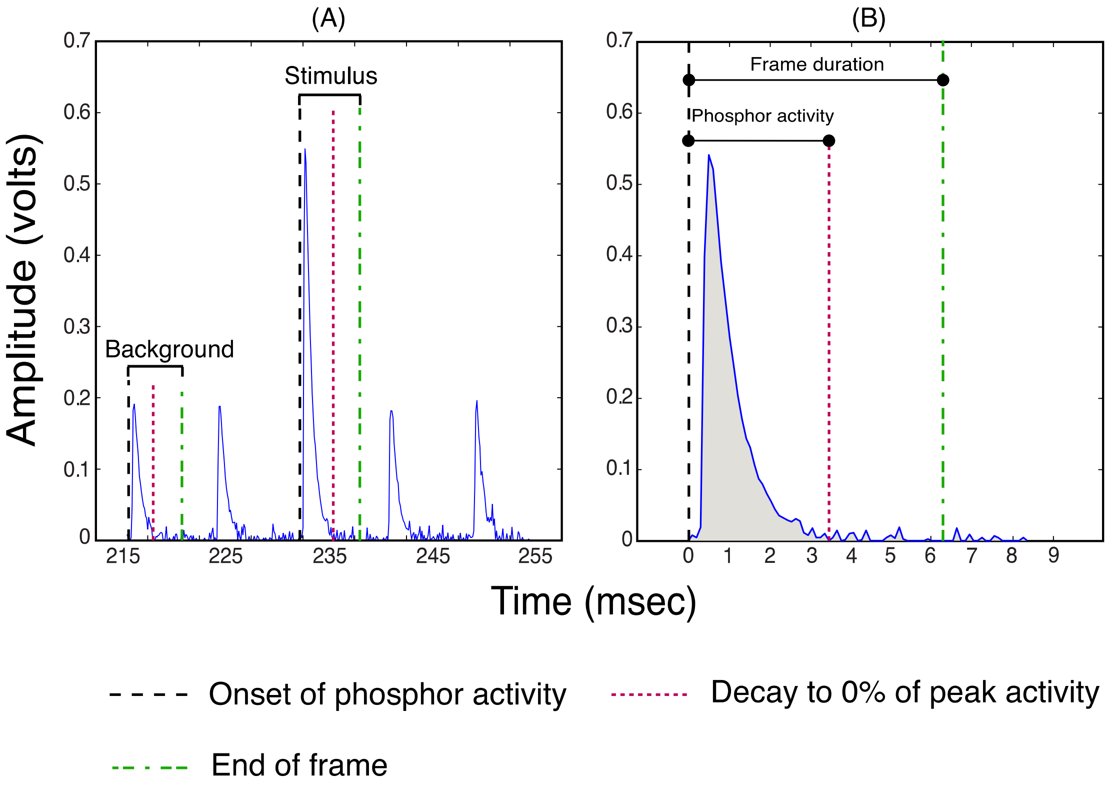

Figure A1 (A) Example OTR-3 trace. The start of phosphor activation (black line) together with the point at which phosphor activity decays to 0% of peak emission (red line) were manually selected. The temporal limit of each frame (green line) was automatically calculated using the refresh rate. (B) Phosphor activity within a complete frame was plotted using the measurements taken from Plot A. Energy output during phosphor activity (E_p) and within each frame (E_F) was estimated by calculating the area under the OTR-3 trace (grey) up to the points indicated by the red and green dashed lines, respectively.