Max-Planck-Institut
für Mathematik
in den Naturwissenschaften
Leipzig

Achieving precise display timing in visual neuroscience experiments

by

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Preprint no.: 33 2010

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Abstract

In experimental visual neuroscience brief presentations of visual stimuli are often required. Accurate knowledge of the durations of visual stimuli and their signal shapes is important in psychophysical experiments with humans and in neuronal recordings with animals. In this study we measure and analyze the changes in luminance of visual stimuli on standard computer monitors. Signal properties of the two most frequently used monitor technologies, cathode ray tube (CRT) and liquid crystal display (LCD) monitors, are compared, and the effects of the signal shapes on the stated durations of visual stimuli are analyzed. The fundamental differences between CRT and LCD signals require different methods for the specification of durations, especially for brief stimulus presentations. In addition, stimulus durations on LCD monitors vary over different monitor models and are not even homogeneous with respect to different luminance levels on a single monitor. The use of LCD technology for brief stimulus presentation requires extensive display measurements prior to the experiment.

Key words: computer monitors, timing precision, timing errors, CRT, LCD

Accepted for publication in *Journal of Neuroscience Methods* on June 19 2010

1 Introduction

1.1 *Motivation and scope*

Accurate knowledge of the temporal properties of visual stimuli is required in many experiments in visual neuroscience. In this work we analyze the temporal signals of the two most frequently used types of computer monitors, namely cathode ray tube (CRT) monitors and liquid crystal displays (LCD). We discuss the consequences for the accuracy of specifications of stimulus durations, particularly for brief stimuli.

Since in the last decade LCD panels have gained popularity and have widely replaced CRT devices as standard monitors, LCD technology is considered in detail in this work.

1.2 *Temporal signals of CRT monitors*

CRT monitors are widely used in visual neuroscience, and their spatial and temporal signals have been extensively studied in vision science (see, e. g., Sperling, 1971a,b; Travis, 1991; Metha et al., 1993; Robson, 1998; Brainard

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[⋆] I wish to thank Jürgen Jost for encouraging and supporting this work, Henry Tuckwell for assistance with English, Bernhard Englitz for his support measuring the phosphor decay, Michael Becker for his assistance with LCD measurements and for providing the measurement device, Timm Lochmann and Ulrich Steinmetz for inspiring suggestions, the two anonymous reviewers for their comments and corrections, and particularly Thomas Tanner for his collaboration in the LCD project.

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et al., 2002). Here we give a brief summary of their properties.

There are two major technologies used to manufacture CRTs, namely shadow mask and aperture grille. In a shadow mask CRT monitor, tiny holes in a metal plate behind the front glass separate spots divided into three color layers (red, green, and blue) which are covered with a substance called *phosphor*. In aperture grille CRTs the same technology is applied except that instead of small holes, fine vertical wires behind the front glass are used to separate the colors.

Every single dot on a CRT monitor is refreshed periodically. We call the period between two refreshes a *frame*. The visible image on the monitor is defined as a discrete raster of *pixels*. All modern CRT monitors do not map their phosphor points to a fixed pixel matrix but allow one to determine the number of such addressable pixels by the graphics card.

1.2.1 Raster scan

As described in various previous studies (e.g. Sperling, 1971b; Travis, 1991), an electron beam inside the CRT tube scans the raster linewise from left to right, beginning with the uppermost line. When the beam has traversed the rightmost pixel in a line above the last line, it jumps to the first pixel one line below. The duration of this jump we call the *horizontal blank* (b_h). When the beam has passed the rightmost pixel in the last line it jumps back to the leftmost pixel in the first line. The period of time of this jump we call the *vertical blank* (b_v). It is about 5% of the frame. This is repeated periodically in the way that each pixel is scanned once per frame. When the beam reaches a pixel it starts to emit light.

1.2.2 Phosphor decay

Upon stimulation, the luminance of the phoshpor rises rapidly and reaches its maximum almost instantaneously. After this, the energy decays, initially exponentially, later converging to a power law course. The decay is illustrated in Fig. 3; exemplary measurements can be found in vision science literature (e. g. Vingrys and King–Smith, 1986, Fig. 3). Because of the non–exponential time–course, specifications of decay constants, although convenient, are not appropriate for decays to low percentages of the maximum. Usually, decay times to the 10% level are specified.

The persistence of the luminance signal depends on the phosphor type. Travis (1991) reports spectral peak decay times to the 10% level from around 30 μs (P–4 phosphor) up to several seconds (P–26 phosphor). For the frequently used P–22 phosphor, the decay time ranges from 1.5ms to 6ms (Sherr, 1993, p. 91).

Note that the phosphors for red, green, and blue within one monitor can have different decay times. Vingrys and King–Smith (1986) show that these decay differences can produce unwanted luminance transients for switches of screen colors between equiluminous stimuli and estimate this effect with a temporal response model of the visual system. The authors introduce methods to minimize these artifacts. In addition, Birch et al. (1992) introduce a method which uses luminance noise to cope with such artifacts (see Flanagan and Zele, 2004, for an implementation).

Commonly used refresh rates are 75 Hz to 120 Hz, but a few monitors (e. g. Iiyama HM204DT) offer a refresh rate range between 50 Hz up to 200 Hz. In the last few decades, monitor manufacturers successfully implemented shorter phosphor decays to reduce motion blur and after images, but due to the pulsed signal, perceivable flicker can occur for fast phosphors. Therefore, the maximal refresh rates increased steadily up until the termination of CRT production. Note that refresh rates greater than 100 Hz are the best trade off between refresh rate and the visual response (Zele and Vingrys, 2005).

CRT monitors need 45 minutes to one hour to *warm up* (see, for example Metha et al., 1993; Brainard et al., 2002) during which the luminance significantly increases and there may also be color changes.

As Metha et al. (1993) state, the luminance in the center of a CRT monitor is most intense and drops off significantly at more peripheral locations. Therefore, stimulus presentations may have to be restricted to small regions around the screen center.

1.3 Temporal signals of LCD monitors

In contrast to CRTs, liquid crystals do not emit light directly but are placed in front of a light source called *backlight*.

The points on the LCD panel are composed of a layer of orthogonal molecules between two polarizing filters and two electrodes. Applying a voltage to these electrodes aligns the molecules. The amount of applied voltage determines the opacity of the point. In so–called “normally white” monitors, a voltage application makes them more opaque while the absence of voltage lets the highest amount of backlight pass. “Normally black” monitors, analogously, are maximally impermeable for the backlight if no voltage is applied.

Unlike most CRT monitors, LCD devices have a *native resolution*, and the pixels set by the video hardware need to map this resolution.

1.3.1 Screen refresh

The CRT screen layout conforms to the raster scan which does not exist in LCD panels. However, because of existing monitor control protocols for CRT devices, LCD monitors are controlled in the same way as described in 1.2.1.

While the signal of a stimulus that is presented for more than one frame on a CRT monitor is pulsed for every frame, the corresponding LCD signal remains constant (except for possible backlight modulations).

In contrast to the wide range of CRT refresh rates, LCD refresh rates are fixed, usually to a single refresh rate as little as 60 Hz. Some LCD panels support more than one refresh rate, such as the Fujitsu Siemens Scenicview P19 monitor which can be operated either in a 60 Hz or in a 75 Hz mode.

Occasionally, LCD manufacturers specify ranges of supported refresh rates, for example 60 Hz to 85 Hz. Nevertheless, the LCD monitor will map any frequency applied via the analog output unit of the graphics card to its active native refresh rate.

Up to now, we assumed that LCD monitors provide a constant signal if no luminance transitions are operated. In the following, it will be shown that this assumption is an oversimplification.

There are two dominating LCD backlight technologies: cold cathode fluorescent lamps (CCFL) and light–emitting diodes (LED). For both technologies, backlight luminance modifications need to be realized by pulse width modulation which results in a high frequency backlight modulation (see, for instance, Becker, 2008). Typical dominant frequency values for the backlight which we found in our measurements in this work and in a previous work (Elze and Tanner, 2009) range between 160 Hz and 200 Hz. The amplitude of this modulation is higher, the lower the backlight luminance. For some monitors this amplitude is close to zero for a backlight setting of 100% (see, for instance, Fig. 2c). These backlight modulation frequencies are far from the critical flicker frequency and the resulting modulations are frequently neglected in the LCD literature.

For measuring the temporal characteristics of LCD devices, however, it is necessary to disentagle the backlight modulation from the luminace transition. To achieve this, we measured constant signals that correspond to the target luminance of each transition separately and calculated the quotient of the constant measurement and the transition signal (see Elze and Tanner, 2009, for details).

As with CRT monitors, LCD panels need a warm up time until their backlight and their temporal characteristics stabilize (Liang and Badano, 2007).

1.3.2 Response times

Up to now, we have only considered static luminances. The typical situation in a visual neuroscience experiment, however, is a dynamic display with onsets and offsets of stimuli. Luminance transitions on LCD monitors are processed differently from those on CRTs.

On a CRT monitor, the luminance change is completed in the subsequent frame after the arrival of the graphics adapter signal. From the next raster scan the phosphor is addressed with the parameters of the target luminance.

LCD devices, on the other hand, need to change the voltage of the respective pixel. Upon this voltage change, the molecules align. The duration of this luminance transition due to this alignment is called *response time (RT)*.

The RT has a strong influence on the controllability of presentation durations on LCD monitors. In this work, we follow ISO 9241 and define RT to be the interval between 10% and 90% of the luminance transition. By exemplary RT measurements, the problems of the LCD temporal response will be demonstrated later on in this work.

2 Methods

2.1 Monitors

Response signals of a Dell 3007 WFP (Dell Inc., Round Rock, Texas, USA) and an Eizo CG 222 W (Eizo Nanao Corporation, Hakusan, Ishikawa, Japan) were measured and respective response times calculated by the division method (Elze and Tanner, 2009). The monitors were measured under their native refresh rate (60 Hz) and their native resolutions (Eizo: 1680 dots [473.8 mm] × 1050 dots [296.1 mm]; Dell: 2560 dots [641.28 mm] × 1600 dots [400.8 mm]). As response times are known to decrease with increasing monitor temperatures (Liang and Badano, 2007), all measurements were performed after a warm–up time of at least one hour.

The monitors were controlled by a Pentium 4 PC with an NVidia GeForce 6600

GT (NVidia Inc., Santa Clara, CA, USA) graphics adapter. The monitors' controllers labelled "brightness" (which control the backlight luminance) were set to 100%. Five independent measurements per condition were performed with an optical transient recorder OTR–3 (Display Metrology & Systems GmbH & Co. KG, Karlsruhe, Germany[1]). Each measurement trial contained a time interval of one second at a resolution of 10,000 sampling points. The maximal photometer voltage of the OTR was 5 V, its noise equivalent power < 5 mV. The dynamics of the device, defined as the ratio of noise equivalent power and maximal voltage, was greater than 1,000. The aperture size of the OTR was 3 mm which covered about 11 pixels on the Eizo and 12 pixels on the Dell monitor.

Note that the Dell manual specifies a "14 ms typical (black to white)" and an "11 ms average (grey to grey)" response time, while the Eizo manual specifies a response time of 16 ms.

2.2 Procedure

The measurements were performed according to the standard ISO 9241. In the following we denote the RGB value sent to the graphics card in order to control color and luminance of the monitor by the unit rgb_8, where n rgb_8 (n integer, $n \in [0, 255]$) means a digital 8–bit RGB triplet (n, n, n). As suggested by the ISO standard, the transitions between the gray levels corresponding to 0 rgb_8, 63 rgb_8, 127 rgb_8, 191 rgb_8, and 255 rgb_8 (max. luminance) were recorded. For the recordings, the OTR sensor was placed over a test patch

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[1] http://display-messtechnik.de/typo3/fileadmin/template/main/docs/OTR3-6.pdf

covering 20% of the monitor's width (Eizo: 336 pixel, Dell: 512 pixel) in the center of the screen on a black background (r,g,b = 0,0,0). The luminances of the black background, measured by an X–rite eye–one Display2, were 0.3 cd/m^2 (Eizo) and 0.2 cd/m^2 (Dell).

For response times between two luminance levels l_1 and l_2, the patch was presented for 10 frames with luminance l_1 followed by 10 frames with luminance l_2, periodically. Fig. 1 shows the raw data of an exemplary measurement (1 second, 10,000 sampling points).

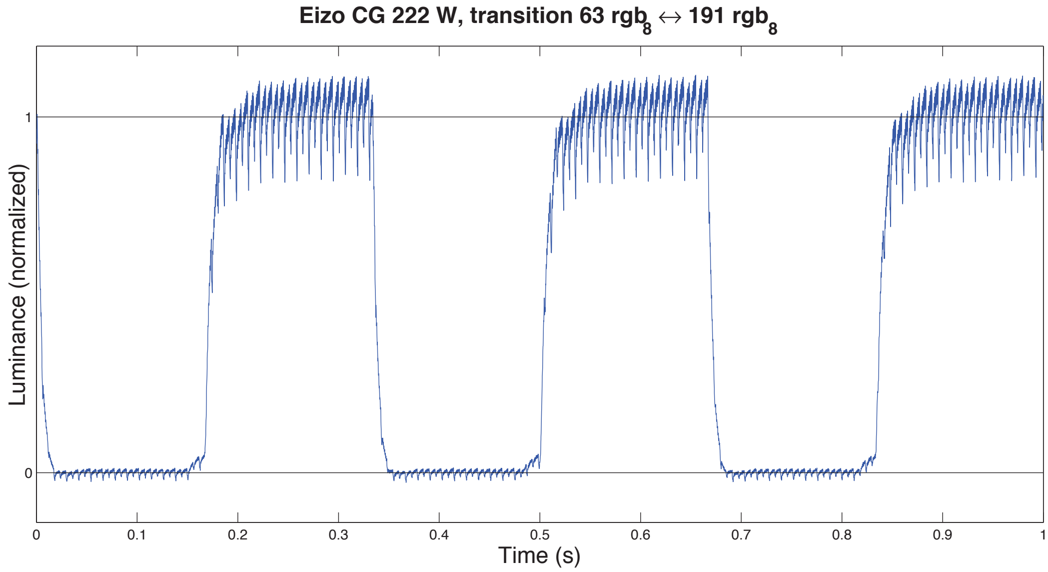

Fig. 1. Exemplary OTR recording of the 63 rgb$_8$ ↔ 191 rgb$_8$ transition of the Eizo monitor. The raw, unprocessed one–second signal is shown. The ordinate values have been converted from voltage to normalized dimensionless luminance.

Stimulus presentation was controlled by FlashDot (Elze, 2009), available at http://www.flashdot.info. The FlashDot script used for the measurements is available at http://monitor-metrology.origo.ethz.ch/.

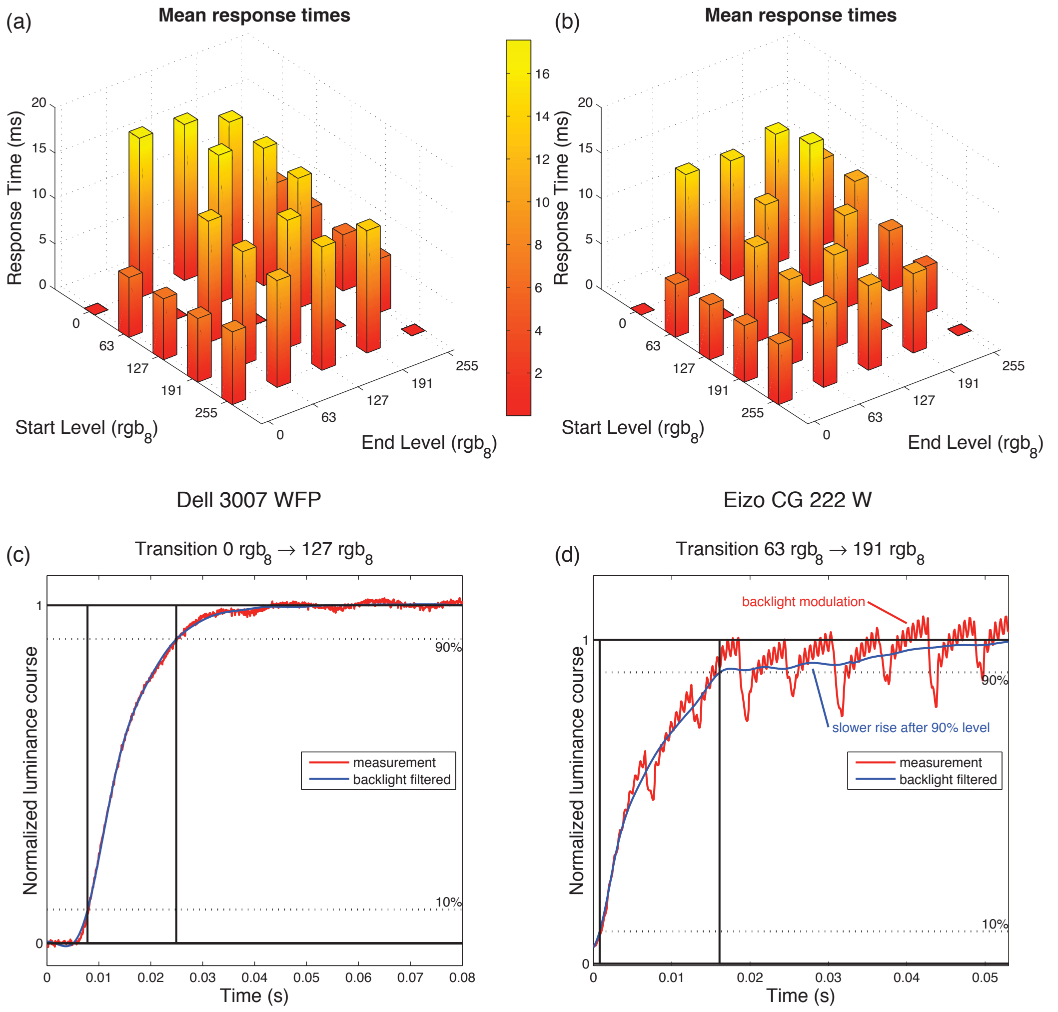

Fig. 2. Luminance transition measurements of two LCD monitors (left hand side: Dell 3007 WFP, right hand side: Eizo CG 222 W). (a) and (b) show average response times over five independent measurements for different luminance transitions. (c) and (d) show exemplary response signals (the measured signal and the remaining signal after backlight removal) of the respective monitor. The two vertical lines in (c) and (d) mark the luminance transition between 10% and 90%, that is, the interval for response time measurement.

3 Results

Fig. 2 shows the means over five independent response times measurements for each monitor (panels (a) and (b)). The average standard deviations of 0.07

ms (Dell) and 0.14 ms (Eizo) confirm a high measurement reliability. Panels (c) and (d) show exemplary rising transitions for each monitor. The interval used for the reponse time determination (according to ISO 9241 between 10% and 90%) is marked by the two vertical lines in each plot. For the plots, the OTR signals have been normalized: The lower luminance level was set to zero and the higher level set to one.

While the backlight modulation amplitude of the Dell monitor was close to zero (Fig. 2c), there is a noticeable modulation for the Eizo device (marked in Fig. 2d), although the backlight luminance of both monitors was set to 100%. Also note that the Eizo luminance rises distinctly slower after the 90% level (that is, outside the response time interval according to the ISO standard) than between 10% and 90%.

4 Discussion

4.1 Sum of frames (SOF) duration specifications and their pitfalls

A very simple and frequently used way to specify stimulus durations is to sum up over the frames for which a stimulus is shown. In the following, we call this specification the Sum of Frames (SOF) method. Fig. 3A illustrates the implicit assumption of the signal course when this method is used: The SOF method is a correct timing calculation procedure if the signal is rectangular, starting from the first frame and ending after the last frame.

CRT literature discussed above and our own LCD signal measurements show that neither for LCDs nor for CRTs these SOF conditions are met. As for CRT

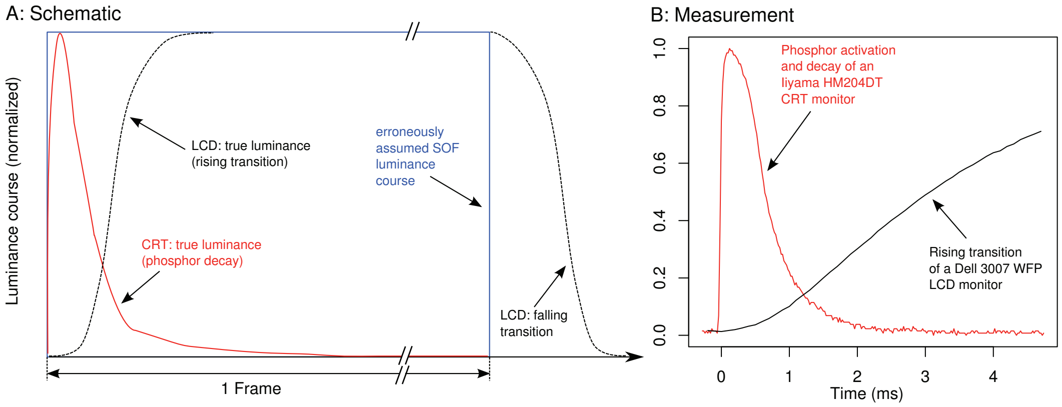

Fig. 3. **A**: Schematic of the erroneously supposed luminance course of a single pixel when calculating presentation durations by summing up frames (SOF) together with an outline of real luminance courses of CRT monitors and LCD monitors (liquid crystal response). Note that the LCD transition times vary drastically between different monitors and between different luminance levels within a single monitor. The transition can exceed one frame. **B**: Exemplary CRT and LCD signal measurements. The luminance transition signal of the red channel from 0% to 100% is shown. The P22 phosphor of the Iiyama HM204DT (Iiyama Corporation, Asakusa-Bashi Taito-Ku, Tokyo, Japan) CRT monitor is activated almost instantaneously and decays to zero within 2 milliseconds, whereas the luminance transition signal of the Dell LCD monitor is still far from reaching its target luminance after twice this time.

monitors, the signal within each frame is a single pulse the duration of which is independent of the frame duration and only determined by the phosphor decay characteristics. For phosphors of most contemporary CRT computer monitors, the luminance decays to zero after a few milliseconds. As Fig. 3B shows, the P22 phosphor of modern CRT monitors enables a luminance increase to the 100% level almost instantaneously (after 0.18 ms for the signal shown in the figure) while our measured LCD rise times shown in Fig. 2 vary between five and 17 milliseconds. Up to exactly the end of the frame, the LCD signal is still on the upper luminance level. In the subsequent frame it decays to zero. See Fig. 3A for an illustration.

Fig. 3B substantiates this schematic by exemplary signal measurements. The measurement methods are the same as specified in 2.1 except that instead of a rectangular patch ten subsequent horizontal lines centered vertically on the screen have been measured. The signals in the figure are normalized between 0 and 1.

4.2 LCD vs. CRT

Are LCDs equally suitable for visual experiments which require precise timing and brief stimulus durations? The bar plots in Fig. 2 indicate one of the LCD drawbacks: The heterogeneity of the response times between different luminance levels makes different duration specifications for different luminance transitions necessary. That means, a stimulus which is composed of many different luminance values would not have a uniform presentation duration: Some parts of it are presented for longer times, other parts for shorter times. Frequently used stimuli composed of many different luminance levels are, for instance, sinusoidal gratings, gabor patches, or natural scene photographs.

During onset and offset of such composed stimuli, the intermediate appearances of these stimuli may differ in their relative luminance distributions. Fig. 4 illustrates this for the onset of a hypothetical patch stimulus which is composed of four different luminances on a black background on the Dell 3007 WFP monitor. In addition, the points in time are indicated at which the corresponding patch signal on a CRT monitor with the same refresh rate as the

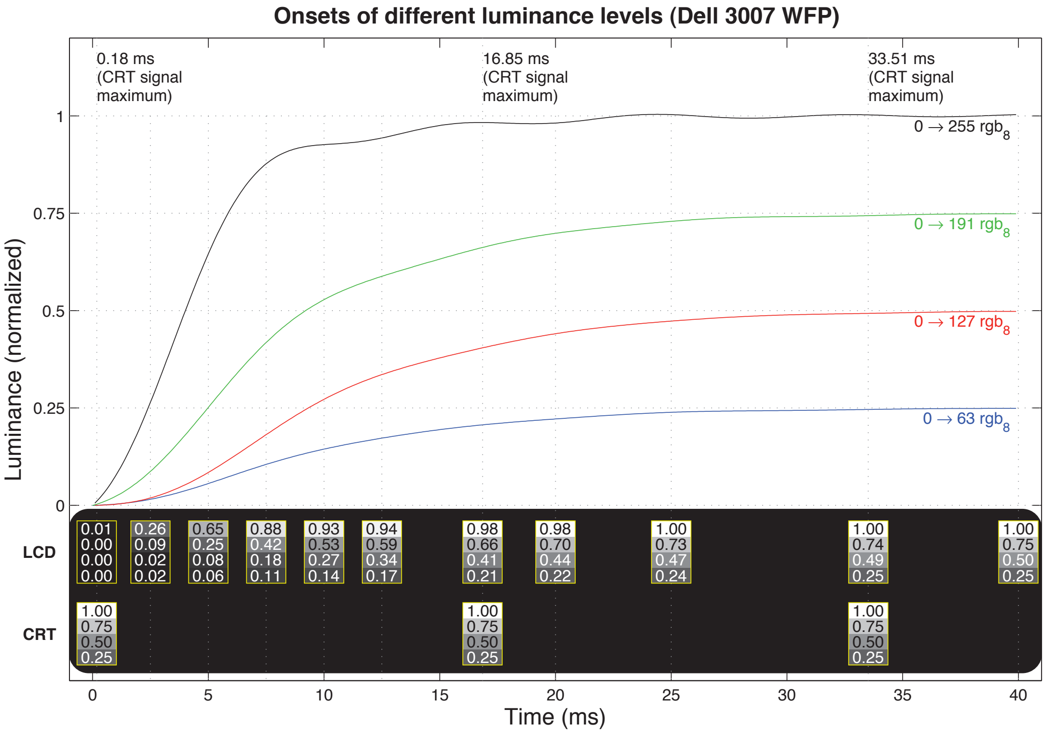

Fig. 4. Illustration of the luminance course of a patch stimulus which is composed of four different luminances (25%, 50%, 75%, and 100% of maximum of the normalized luminance range) over 40 ms after the patch onset at $t = 0$. The four curves are normalized OTR signals after backlight removal taken from the Dell 3007 WFP measurements described in 2.2. Below the curves, the luminance of a hypothetical patch is shown at certain discrete time values. The upper row shows the patch appearance on the Dell LCD monitor. The numbers on the four stripes of the patch denote the relative luminances taken from the curves at the corresponding point in time. The lower row shows a hypothetical test patch on a CRT monitor with P22 phosphor. The CRT signals reach their maxima 0.18 ms (value obtained from the measurement in Fig. 3B) after each frame onset and decay to the black point within about 2 ms.

LCD (60 Hz) would be maximal. Obviously, on the LCD monitor it takes more than two frames until all four patch components reach their target luminance. In addition, one can see that the patch components have differently long luminance transitions. Therefore, the relative luminance distribution within the patch varies for intermediate patch appearances.

The manufacturers' specifications of the two measured LCD panels stated only one or two RT values for each monitor (see 2.1) and are therefore insufficient to characterize the devices for an application in vision research.

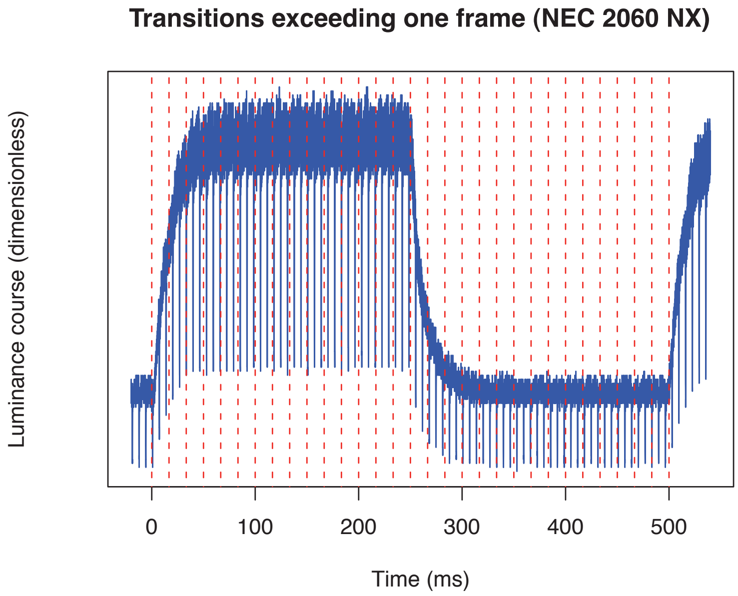

Fig. 5. Periodical 25%↔50% transition on a NEC 2060 NX LCD (NEC Corporation, Minato-ku, Tokyo, Japan) monitor, each level displayed for 15 frames. The vertical dashed lines indicate the frame boundaries. Obviously, it takes more than one frame for each transition. Note the strong backlight modulations.

Fig. 5 illustrates a further risk: For some LCD monitors the luminance transitions may exceed one frame. The plot in the figure shows a photomultiplier (RCA 1 P 28, aperture size: 3 mm) signal of a 25%↔50% transition which was recorded by a Tektronix TDS410A oscilloscope.

Stimulus durations on computer monitors can only be controlled by presenting the stimuli for full frames. Hence, the refresh rate of the monitor is a crucial determinant for timing controllability. The higher the refresh rate the higher is the temporal resolution and the more different stimulus durations can be adjusted. In addition, Zele and Vingrys (2005) demonstrated for CRTs that the deviation between SOF and the true duration (in terms of duty cycle) decreases as frame rate increases and they recommend frame rates > 100 Hz. While contemporary CRT monitors usually support a wide range of refresh rates up to 200 Hz, LCDs support only a few, most of them even only one native refresh rate, usually as low as 60 Hz. That means, their temporal scope of operation is clearly restricted.

4.3 Timing within one frame

The SOF measure completely neglects timing differences within a single frame. If synchronization of the graphics card signal to the vertical blank of the monitor is active the beginning of a frame can be determined, but it is equal to the beginning of the stimulus presentation only if the stimulus starts at the leftmost pixel of the uppermost line on the monitor raster. For both LCD and CRT monitors, the displayed content is built up line by line from top to bottom, whereas the timing differences within each single line are negligible.

The duration of traversing a single line and the horizontal blank are usually known, so the temporal onset of the stimulus can be easily calculated relative to the frame start.

The experimenter should keep in mind that the time difference between the leftmost pixel of the first line and the rightmost pixel of the last line is almost one frame (precisely, one frame minus the time of the vertical blank, approximately 95% of one frame).

4.4 Stimulus timing, early filtering, and the window of visibility

There is a long history of research on the temporal resolution and early filtering mechanisms of the visual system. Bloch (1885), for instance, stated that the detectability of short visual stimuli depends only on their energy, that is the product of luminance and duration (*Bloch's law*). In this case, one could ignore the timing specification models but needed to integrate over the luminance instead.

Bloch's law and related filtering properties of the early visual system (e.g. Watson, 1986) might raise the question of stimulus presentations which have "perceptual" durations that are not multiples of frames. Robson (1998), for example, reports that halving the luminance in the last frame of a stimulus that extends over a number n of frames on a CRT screen can result in a retinal response the decay of which occurs halfway between the decay of the signal of $n-1$ and n full luminance screens. That means, luminance changes can simulate the effects of duration changes.

Early low pass filters of the visual system in accordance with Bloch's law could integrate the total energy so that the exact signal shape could be neglected. If the filtering kernel convoluted with the signal would be broad enough (resp. the refresh rate high enough), the consideration of the pulsed nature of CRT signals could become irrelevant since the responses of the filtered signal would be indistinguishable from the responses of a constant signal with equal energy.

In accordance with the concept of early lowpass filters, it has been argued that the temporal resolution for luminance changes of the fovea is limited to a critical flicker frequency (CFF) of about 50 Hz to 60 Hz, (e. g. de Lange, 1958; Brown, 1965).

Such early filtering approaches, however, question the whole practice of specifying short durations of stimuli. They require not only very accurate models of the filtering properties of the early visual system but also a discussion by the experimenters why their modified input signals should be interpreted as different durations at all and why the energy distribution can be ignored.

Even if we rely on an early filtering model, it is unclear which frequency to apply for such an early filter. Chichilnisky and Kalmar (2003), for example, show that the temporal CRT driven response can have an impact on cellular outputs. Zele and Vingrys (2005) analyzed the power spectrum of stimuli presented on CRT screens and conclude that artifacts introduced by the discrete sampling of the phosphors in the range of 60–80 Hz can elicit neural responses although they are perceptually invisible. Keating et al. (2001) found fundamental differences in multifocal electroretinogram waveform for identical stimuli displayed on a CRT monitor vs. an LCD projector, although for both devices no flicker was perceived. Moreover, it could be shown that the visual system can adapt to frequencies beyond the CFF, that is that flicker can be processed without conscious perception (Shady et al., 2004).

Zele and Vingrys (2005) focus on the concept of the *duty cycle* of the luminance signal, that is the ratio of the ON–period to the desired stimulus duration. The authors demonstrate effects of the limited duty cycles of CRT phosphors on neuronal responses. In the variety of vision science experimental studies quite different refresh rates and therefore different duty cycles are used. A stimulus duration of 16.7 ms according to the SOF measure can be realized, for instance, by a 60 Hz and by a 120 Hz refresh rate, but the duty cycle of the latter signal is twice of that of the former signal for the same phosphor, and therefore, the higher the frame rate, the closer is the signal to the continuous signal assumed by SOF (Zele and Vingrys, 2005). That means, the same assumed stimulus duration might result in different neuronal responses.

Zele and Vingrys (2005) were concerned with CRT devices only. But their duty cycle concept raises interesting questions about LCD signals as well: Strong LCD backlight modulations make it possible to regard ON and OFF periods of LCD luminances. Therefore, it might be useful to analyze the frequency spectrum of the backlight in more detail.

We recorded one second of the upper level of the transition signal in Fig. 2(d). Fig. 6(a) shows 100 ms of this recording. The signal was normalized by division by its mean. Fig. 6(b) shows a part of the normalized power spectral density (PSD) of this signal, estimated by the periodogram method. The dominant backlight frequency can be identified as 166 Hz. In addition to its higher frequency aliases, one can see a substantial power of the frequency 1,524 Hz, which is visible in Fig. 6(a) as the superimposed high frequency ripple. Furthermore, the signal in Fig. 6(a) shows that every other trough of the dominant frequency is deeper than its corresponding neighbor. This alternation of deeper and less deep troughs is reflected in the substantial power of 83 Hz (half the dominant frequency), visible as the first peak in Fig. 6(b).

Watson et al. (1986) approximate the limits of visual sensitivity to spatial and temporal frequencies by a “window of visibility” within which visual stimuli are perceivable. Zele and Vingrys (2005) apply this concept to the resolving

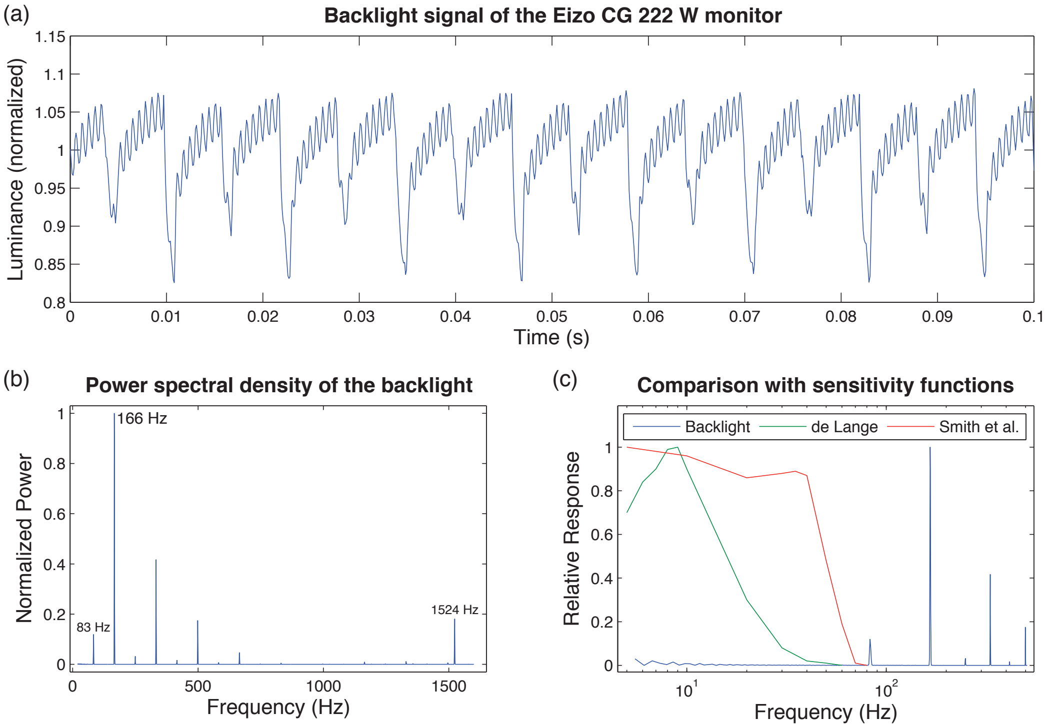

Fig. 6. (a) Backlight signal of the Eizo monitor, recorded from a constant signal at the upper level of the transition shown in Fig. 2d. (b) Normalized power spectral density (PSD) of the signal shown in (a). (c) Comparison of the PSD shown in (b) whith de Lange's psychophysical temporal sensitivity function and that of a horizontal cell (H1) from Smith et al. (2001). The sensitivity functions in (c) are redrawn from a similar plot from Zele & Vingrys (2005, Fig. 5) who related these functions to the PSD of a CRT signal. Note the log scaling of the abscissa in (c).

capacity of neurons and propose a *neural window of visibility*. Based on the concepts of perceptual and neural windows of visibility, they investigate CRT signal artifacts caused by the duty cycle due to phosphor decay. In their Fig. 5, the authors compare the PSD of a CRT luminance transition signal to a psychophysical temporal sensitivity function from de Lange (1954) and that of a horizontal cell early in the visual process (Smith et al., 2001). Their figure shows that substantial PSD components, although being invisible, may become detectable by neurons.

Fig. 6(c) reproduces Fig. 5 from Zele and Vingrys (2005) but relates the two sensitivity functions to the LCD backlight signal instead of the CRT transition signal. It can be seen that for the Eizo backlight all substantial PSD components are outside the perceptual as well as the neural windows of visibility. However, the 83 Hz frequency (first peak) comes close the the neural sensitivity of that particular neuron. Note that different monitor models differ a lot in their backlight properties and there might be LCD panels with substantial backlight components which fall within the windows of visibility for certain neurons in the visual system.

Taken together, independent of possible early filtering mechanisms, if experimenters make duration specifications, these need to be related to the real physical durations of the stimuli. If "perceptual durations" are assumed, this needs to be explicitly stated in the study, together with the corresponding perceptual model.

4.5 Relevance of the timing misconceptions for visual experiments

In considering the effects of duration misspecification, one has to agree on an estimation of the timing specification error. As a working model, let us define the stimulus duration on CRT monitors between the onset of the stimulus (beginning of the first frame) and the time when the luminance has decayed to nearly zero in its last frame. Let f denote the frame duration and p the phosphor decay time (a few milliseconds), then the correct stimulus duration t_c would be given by

$$t_c := \mathrm{SOF} - f + p$$

(Bridgeman, 1998), hereinafter called *Bridgeman model*. In the following, we call the erroneously specified SOF times t_s.

Obviously, the deviations between t_s and $t-c$ are largest for stimulus durations of only a few frames for which the difference is almost one frame: $t_s - t_c = f - p \approx f$. This can be relevant in visual perception experiments: Some perceptual studies demonstrate that duration differences of only 5 ms can drastically change experimental results. For example, Herzog et al. (2003) demonstrated that an increase of target duration from 10 ms to 15 ms can result in an increase of detection performance of about five times.

That means, if experimenters would try to reconfirm such misspecified CRT results by using highly precise mechanical shutters instead of CRT screens, they were likely to fail, and $t_s = \mathrm{SOF}$ specifications in modern CRT studies cannot be compared with classical experimental results obtained by tachistoscopes. Note that most modern tachistoscopes also suffer from trigger delays, build up times and a hysteresis on offset, but are an order of magnitude faster than LCD panels.

Not only are comparisons between different studies made difficult but it is possible that the errors result in invalid conclusions within a *single* study. This can be the case if *statistics over presentation durations* are computed. Even simple statistics as arithmetical means or standard deviation calculations over stimulus durations are severely impaired for t_c vs. t_s. First of all, the calculated presentation means will be much lower for t_c. In addition, presentation time comparisons between different conditions that contain relative changes between different experimental conditions have to be recalculated.

An implicit assumption of such duration statistics is the proportionality of the durations, that is, a time computed by SOF for a presentation of two frames is twice as long as a time for one frame and so on. An important property of t_c is that it extinguishes this proportionality: Presentations for one frame yield duration $p \ll f$, for 2 frames a duration of $p + f$, for 3 frames $p + 2f$ etc.

More complicated statistics over presentation durations include psychometric function fits and model comparisons. Here, the choice of the duration calculation model may also influence statistical results, as the following example will show. Imagine a simple stimulus detection task where a two alternative forced choice answer (stimulus present or absent) needs to be given. The stimulus duration varies between 0 (no stimulus shown) and 10 frames on a CRT monitor with a refresh rate of 60 Hz.

Imagine two similar experimental results in which a subject gave 100 present/absent reports for each of these durations. The first result, given as number of "present" reports, is {50, 52, 55, 58, 67, 75, 85, 92, 95, 97, 97} for the respective presentation duration of {0, 1, 2, ..., 10} frames, the second result differs slightly for brief durations: {51, 50, 53, 57, 67, 74, 86, 91, 95, 97, 97}.

Fig. 7 shows the detection reports for both hypothetical results for both the SOF and the Bridgeman method with $p = 3.7$ ms. In addition, four–parametric logistic function fits according to the maximum likelihood method (see Wichmann and Hill, 2001, for details) are shown, where one of the parameters represents a horizontal shift of the function. The functions were allowed to vary between 0.5 (guessing) and 1 (perfect detection). Although the parameter space for the function fits contains horizontal shifts, the maximal likelihoods

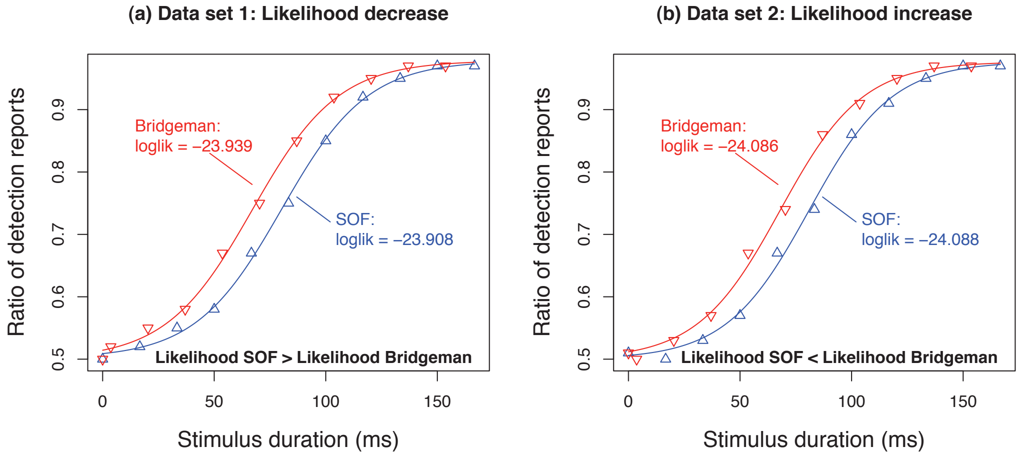

Fig. 7. Two hypothetical data sets of a stimulus detection experiment together with their psychometric function fits and according maximum likelihood estimations for two different duration specification methods. “SOF” denotes the frequently applied sum of frames method, “Bridgeman” the specification model proposed by Bridgeman (1998). “loglik” denotes the logarithm of the likelihood of the fitted curve, calculated according to Wichmann and Hill (2001). Whereas for data set 1 shown in (a) the SOF likelihood is larger than the likelihood of the Bridgeman method, for data set 2 (b) the opposite is the case.

are different for the two duration specification methods. For data set 1, shown in (a), the maximum likelihood for the SOF method is greater than that of the Bridgeman method, where as for data set 2, shown in (b), the opposite is the case.

Although both data sets differ only slightly from each other and only in the area of lower confidence (detection rate between 0.5 and 0.6), for one data set the likelihood decreases when the more accurate Bridgeman model is applied, whereas it increases for the other. Maximum likelihood estimations are the base of many frequently applied model comparison methods in vision science, such as χ^2 likelihood ratio tests or comparisons based on information criteria like AIC (Akaike information criterion; Akaike, 1974) and BIC (Bayesian information criterion; Schwarz, 1978). Obviously, all these methods can be affected since switching between two duration specification methods yields unspecific maximum likelihood changes.

As stated above, Bridgeman's t_c model is a better description of presentation duration than the SOF measure on CRT monitors, but it does not take into account the strictly non–uniform energy distribution of CRT signals. In addition, it is unclear how to define the point in time when the phosphor decay is finished.

Under appropriate dark adaptation human subjects can perceive even single photons (Hecht and Hsia, 1945), so the phosphor decay time could even exceed the frame duration dramatically. DiLollo et al. (1994) refer to the fact that luminance measures of phosphor decay (in their case phosphors in oscilloscopic displays) need not be valid measures for *visible persistence* since in the noise of the measuring device residual signals can be hidden that are visible to the human observer. The sensitivity of the eye to this residual signal depends on its adaptation level. Groner et al. (1993) show for a special phosphor type (P31) that its visible persistence can last several hundred milliseconds. Therefore it is problematic to define an endpoint of the decay signal.

No matter what signal endpoint is defined, the phosphor decay of a single pixel is not related at all to the monitor's refresh rate. Therefore, an SOF specification of a single frame stimulus is unrelated to the true stimulus duration.

I suggest that CRT presentation times be specified only by the number of frames and that statistical calculations with stimulus durations be omitted unless the influence of the signal shape and energy distribution is explicitly discussed or taken into account. On the one hand, it has been previously shown (Zele and Vingrys, 2005) that effects of the signal shape and energy distribution are minimized for CRT refresh rates greater than 100 Hz and that photoreceptors and their post–receptoral pathways are hardly effected by stimuli presented at such refresh rates. On the other hand, most LCD panels allow frame rates of only 60 Hz, which makes considerations discussed above relevant for experimental applications of this technology.

5 Summary and conclusion

The luminance signals of CRT and LCD monitors differ considerably from each other. Stimulus duration specifications based on counting frames (SOF method) are not suitable for either of the technologies, especially if stimuli are presented only for a single frame.

The pulsed CRT signal challenges duration specification methods because there is an abrupt stimulus onset and a gradual stimulus offset down to zero luminance in each frame. LCD panels, on the other hand, are sample and hold devices. Stimuli are relatively constant on them between their onset and offset, as assumed by the SOF method. However, the exemplary LCD transition measurements in this work indicate that the SOF method can be deficient for LCD monitors as well because rising and falling transitions can be asymmetric. Furthermore, for some LCD panels luminance transitions exceed one frame.

The results presented in this work suggest that the commonly applied SOF measure neglects the signal shape and other important properties of the two display technologies. Therefore, it is suggested to specify the number of frames a stimulus is presented and not to calculate presentation durations. If presentation durations will be specified, it is necessary to state the exact method how they are estimated.

Because of the timing model dependence of statistical data analysis, one should avoid calculating statistics over brief stimulus durations unless the chosen timing model is explicitly discussed.

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