Do you see what I mean?

Computer driven tachistoscopes: an empirical comparison of the CRT, LCD, LCD/DLP Projectors and a lamp modified multi projector system(Beam).

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Abstract
Benchmark data for several technologies for presentation of visual stimuli are discussed. A new technology that obtains it's precision by switching of an array of LEDS is described in full. The article concludes with precise recommendations for the process of choosing an optimal visual stimulus device depending on the experimental requirements.

Introduction

With existing technologies ever improving and complete new technologies arriving, it is important to understand the differences between the many present possibilities for visual stimulus presentation. In terms of physical specifications, there are quite substantial differences among the several video output apparatus like CRT displays, LCD panels, LCD projectors, DLP projectors. Not only the physical specifications matter, it is essential to assess the overall performance in combination with the controlling software. An in-house developed Lamp modified multi projector system is a case in point. Especially short stimulus presentation and sequences of consecutive presentations require well adjusted physical and software properties. In this paper we will compare various display technologies which are carefully selected for the best performance and discuss their specific advantages and disadvantages.

Over the last decade computer driven stimulus presentation devices, as a replacement of the cabinet (shutter based) tachistoscope, have become a major mode of presentation. The display device discussed mostly in the context of the tachistoscope replacement is the Cathode Ray Tube (CRT) display. The CRT display has however some specific characteristics. The screen is built up in horizontal scan lines which results in unclear stimulus durations (Bridgeman, 1998). In spite of these far from ideal CRT characteristics Hunter et al. (Hunter, Duboff, Oscar-Berman and Mueller, 1999) concluded that perception of visual stimuli presented as continuous images on a conventional tachistoscope may be equivalent to perception of visual stimuli presented as pulsating images on a CRT. Gradually however the CRT is being replaced by the Liquid Crystal Display (LCD) panel. Since the CRT display cannot be used in some experimental settings like the fMRI scanner or in the neighborhood of TMS equipment, this process will continue and CRT displays might soon become obsolete. Projectors or special LCD panels will be used in this case. Therefore it has become mandatory to take a closer look at the broad range of LCD displays.

As mentioned before, an important factor in short stimuli presentation is the presentation software used. Accurate single frame stimulus presentation software is not trivial, especially not for the Windows platform. Software techniques that enable good timing accuracy are now well known (Forster & Forster, 2003), despite many (even commercial) programs that still lack exact stimulus timing. At the University of Amsterdam a freely distributed software package for highly accurate stimulus presentation is used (Wesp Experimentation Stimulus Program). All the data presented in this paper are obtained using WESP as controlling software.
A recent study comparing time resolution of LCD projectors, LCD panels and the good old shutter technology (Wiens et al. 2004) show rather poor performance for the LCD systems. Wiens et al. report both the LCD projector and the LCD panel having substantial variability among trials on all the presentation parameters (duration, initial latency, rise time and relative maximum luminance). Also pictures did not reach full luminance at short target durations (less than 42 ms). Further, some pictures were not shown at all at the shortest duration (12 ms). They concluded that the use of LCD projectors and panels in studies with brief picture presentations is not recommended. Interestingly, these findings are in conflict with the specifications of LCD projectors and LCD panels. To solve this apparent paradox we decided to test some recent display apparatus.

A review of different display technologies

CRT

Cathode Ray Tube (CRT) monitor display was until recently by far the most used device for stimulus presentation. Some researchers however are not aware of it's actual limitations. When you take a closer look at the screen buildup of a regular monitor using a fast photodiode placed on the screen as a sensor, it becomes obvious that the screen is black most of the time. For each location of the screen there is light produced for about 1.25 msec with intervals depending on the screen refresh rate (typically about 13.3 msec or 75Hz). Since this process of activation of a screen is build up from the upper left corner to the lower right corner there is quite some delay between the emission of light form the upper left corner and the lower right corner for the same frame. Since the human eye integrates the light input (at least for conscious experience), one does not notice the actual 'blinking' of the screen at the commonly used refresh rates (the number of single screen buildups or frames per second). An apparent advantage in terms of short stimulus presentations is the CRT's ability to produce high refresh rates. Regardless if the same or another picture is on the screen, the CRT display is refreshed at the fixed refresh rate. To avoid a flickering of the monitor, professional CRT displays can produce high refresh rates in order to let the display appear more stable. At the resolution of 1024 pixels x 768 pixels, refresh rates up to 150Hz can be obtained. In principle this implies that if a stimulus is presented during a single frame followed by a mask during the next frame, the actual time it seems to be exposed is ~ 7 msec. The real time it is on the screen is, as we have seen above, only around 1.25 msec but the time before a mask in the next frame can appear is 7 msec.

LCD panel *Thin Film Transistor*

The Liquid Crystal Display (LCD) technology uses many different types of liquid crystals that are arranged in a panel. Behind the panel there are some tubes to illuminate the panel. The panel consists of a large number of pixels. Each pixel is put together from three sub pixels, each of which has been covered with a red, green or blue filter. So a 1024x786 panel has 1024 x 786 x 3 pixels (>2.3 million sub pixels). Each sub pixel can be controlled electronically to obtain a certain light transmission angle. This angle determines the amount of light that passes through the subpixel. The pattern of different amounts of light of all the (sub) pixels together creates the image on the panel. (For a more detailed description see: See Vincent Alzieu (2002) on the Tom's Hardware website)

With a changed new picture presented on the panel the screen buildup is spatially similar to the screen build up of a regular CRT screen, starting in the upper left corner, make the picture visible. However the time this takes is different (further explained later in the next paragraph). The way a LCD panel handles non changing pictures is quite different compared to the CRT display. The LCD screen simply isn't refreshed at all for non changing pictures. When a change occurs only the relevant pixels are updated. The LCD has a continuous illumination where the CRT uses a (electron) beam traversing the screen. Thus there is no such thing as a frame rate although in terms of screen updates still this concept is used.

An other difference is the time it takes before a pixel reaches maximum luminance. This time, that depends on the type of liquid crystal used is called the rise time; the time needed to clear a pixel (or set of pixels) is called the fall time. The sum of rise and fall rime is also referred to as the response time. In the past decade the type of crystals in use have developed considerably. This has resulted in a dramatic impact on the response times. Whereas response times in the past were even not specified, applications like video and fast moving action games have resulted in manufacturers documenting the actual response times in the technical specification. Some caution is necessary however because actual measurements done in our lab have revealed deviations from the published specifications.

Although the pixels are getting more responsive, the refresh rate for refreshing all pixels on the screen stays a bit behind. Generally the modern LCD panels can only handle refresh rates up to 75Hz. It might be expected that with response times ever decreasing the refresh rate might increase further although for high resolution screens this is a intensive computational process. In principle it would be possible to have no fixed refresh rate and refresh as soon as a change in 'video' memory occurs. However due to the historical background of the software rooted in CRT as display devices with fixed frame rates (= refresh rate) we expect that refresh rates will stay fixed for some time. The implication is that a change in 'video' memory might become visible on the screen with a delay of maximum 13 msec.

LCD projector

In a LCD projector the light is projected through three separated color LCD's (red, green and blue). This technology makes the optics of these projectors a bit more complex, since the three different projections have to be superimposed rather precisely. The general display characteristics of these separate LCD's are the same as for the LCD panel. In brief, also the LCD projectors have a rise and fall time, the time needed to build up the screen or clear the picture of the screen respectively. Secondly also the LCD projector needs the horizontal scan line for the

novel picture buildup. This results in time gaps between the presentation of the upper left corner compared with the lower right corner. Once the picture is presented, it remains continuously on the screen.
The LCD's used are on average as fast as the regular LCD desktop panels, with the latter being the first to profit form new developments. Often, response times for the LCD projectors are hardly documented by the manufacturers. Furthermore the manufacturers seem to focus (understandably) primarily on film and simple PowerPoint-like presentations. This results in projectors that are mostly only accurate for single frame presentation at the 60Hz refresh rate.

DLP projector

The Digital Light Processing (DLP) projector is winning the competition with the regular LCD projector rapidly. A few years ago the DLP technology was mainly used for professional projectors. These professional projectors used three separate DLP chips for red, green and blue light resulting in complex optics. However a much cheaper one chip projector, with simple optics, has become available over the past years making the DLP projector a mainstream product.
The DLP technology consists of a special semiconductor also know as the Digital Micromirror Device or DMD chip. The DMD chip is a highly advanced light switch. The rectangular chip hold over 1.3 million hinge mounted microscopic mirrors. These mirrors represent the pixels of the picture to be displayed. The microscopic mirrors can tilt toward the light source (ON) or away from it (OFF). Since these mirrors can be switched on and off several thousand times a second, the actual brightness of each pixel can be controlled accurate. To introduce color to the picture much of the non professional single DMD projectors use a color wheel in front of the light source to change the color projected on the DMD from red to green to blue. Now the DMD chip handles the brightness for the different colors once at the time, quickly following each other. A major point of interest with these single chip DMD projectors is the speed of the color wheel. The better DMD projectors use a four speed color wheel. This means that at a single refresh rate of 60 Hz, the color wheel spins four times round within the 16.67 milliseconds (actually the colors on the wheel are R-G-B-R-G-B, so the wheel only spins twice). With older projectors using low wheel speeds some people report discerning the individual RGB colors. This phenomenon is known as the "rainbow effect".
The rainbow effect is a potential disadvantage of this system, although in practice with the four speed color wheel we have not yet had any subjects reporting this sensation. The consequence is that for a single RGB sequence at least 4 msec is required (16.67/4). There is however no horizontal scan line. The DMD is able to switch all the mirrors at once, eliminating time lags for different positions on the screen, as seen in the LCD and CRT technology. For a more detailed explanation of the DLP/DMD technology please see the www.DLP.com (a Texas Instruments division) website.

Lamp modified multi projector system (BEAM)

The tachistoscope, developed at the technical department of the Psychology faculty of the University of Amsterdam (UvA) by co-author Bert Molenkamp, is the result of years of development of well defined computerized short stimuli presentation equipment. The system consists of three projectors where the standard lamp is replaced by an array of 10*10 Light Emitting Diodes (LED type). This array of LEDS allows for very fast on-off switching. Typically LEDs switch on and off well within the millisecond. The three projectors and the three LED arrays are controlled by a computer with BEAM software. The computer holds four Nvidia TNT 32 Mb video cards. For each projector a video card plus one video card for the experimenters BEAM control console. The BEAM software uses a Keithley digital I/O card with its own onboard precision timer for controlling the on and off periods of the projectors. The BEAM timing has a millisecond resolution. The projectors are located in a special 3 floor adjustable case to make the pictures of the three projectors align. The software prepares each trial by placing the 3 pictures to be used in the trial on each of the projectors (with LEDS off). This preparation time depends on the memory load and complexity of the picture. The BEAM software makes sure all the pictures to load fully on the projectors. When all the pictures are loaded, the trial starts and the LED array in the projector holding the first picture is switched on for the desired time. When the subsequent second picture is timed the LED array in the projector holding the first picture is switched off while at the same time the LED array of the projector holding the second picture is switched on etc. Overlapping exposures are also possible. The timing precision is within 1 millisecond while the rise- and falloff times of the LED arrays are xx and yy msec respectively. These specs are comparable to the traditional mechanical shutters on slide projectors. However in our experience however these mechanical shutters require extensive maintenance and are quite sensitive to failure. Furthermore a big aperture is advisable with the modern projectors to guarantee equal illumination over the whole screen, which tends to increase the time which is needed to completely open or close the shutters. As a replacement of the mechanical shutter we used polarizing LCD shutters for some time. These shutters are quite fast and have a reasonable aperture. A big disadvantage with these shutters is that they leak about 10% light in the off position. This could be compensated to a certain extent with some additional filters which distorted the color display. All these problems are overcome with the use of the LED arrays as a sort of a shutter. The amount of light produced by these arrays is only 20% of the standard lamp. So the brightness of the picture is rather low compared with other methods. In the current set-up we use backlight screens from Sreentech. A white picture gives a luminance of xx/cm2. This luminance is adequate for very dim environments. Fortunately LED's are getting brighter each day since they start to be used as light source for traffic lights, the backlights of cars / motors and for flashlights.

In this paper we will take a close look at the actual performance of the different display types in real life. With a light sensitive diode in front of the display to be tested and sampled at high speeds we measured the timing characteristics of these displays

BenchMarking Method

In order to get an adequate representation of current display technologies we have put a lot of effort in selecting the best devices of it's kind. With continuously improving technologies these results might be outdated within a year. We therefore strongly suggest to actively search for the best performing displays. It is not sufficient to check the manufacturer's specifications. These specs should be tested with rather easy measurements as described in this section.

To get the best apparatus, we pre selected some models based on their specifications as provided in the technical documentation available on the internet. In the technical specification we especially searched for the fastest response time documented for the LCD panels. For the LCD projector the response time was not specified most of the time. In this case we pre selected the models with the higher vertical refresh rates. Also for the DLP beamers we pre-selected the models with the higher vertical refresh rates. The brands and types of devices we finally selected based on their superior tested performance are given below:

LG 795SC (our lab standard CRT monitor for the past years)
BenQ 767 -12 LCD panel
Sanyo PLC-XT16 LCD projector
ProjectionDesign F1 XGA – 6 DLP projector
Hitachi multi projector system

For stimulus presentation we used a Pentium IV at 1.5 GHz, with a Nvidia G-force FX 5200 video card holding 128Mb video memory. The software used for the stimuli presentation was WESP. This public domain software has proven over the years to be able to present stimuli with single frame accuracy, reliably over many trials. On each display device we presented 100 trials. Each trial was composed of four presentations of a white full screen bitmap. The visual events (within the trial) were shown in the following sequence: 1 refresh white – 1 refresh black – 2 refreshes white – 2 refreshes black – 4 refreshes white – 4 refreshes black – 8 refreshes white.
The trials were presented at a minimum resolution of 1024x768 pixels at 16 bits. Depending on the devices we used the following refresh rates 60Hz (16.7 msec. per refresh) for the DLP and LCD projectors, 75Hz (13.3 msec. per refresh) for the LCD panel and 100Hz (10 msec per refresh) for the CRT. For all the devices tested we will report the maximum refresh rate at which the device worked properly. Furthermore we will report if the single frame presentation reached full luminance. For the Lamp modified multi projector system (BEAM) we made it a bit more challenging using stimuli presentations of 2 msec. white – 2 msec. black – 4 msec. white – 4 msec. black – 8 msec. white. On the start of each trial, simultaneously with the first single frame white picture, a synchronization pulse was sent to the data acquisition computer.
For data acquisition we used a Pentium IV at 2.8 GHz with a Keithley KPCI 3108 AD-converter card in combination with the in-house build (again by co-author Bert Molenkamp) data acquisition/analysis program VSRRP. The data from the photo diode (Vishay BPW21R) was sampled at 20 kHz. The photodiode with a 1kΩ output resistor has a rise time of 3.1 μs and a fall time of 3.0 μs. We used 3 photodiodes which were placed at the upper left corner, in the middle of the screen and at the lower right corner. The three light sensors give the possibility to detect onset differences depending on screen position. Furthermore the three sensors made it possible to detect partial screen build-ups. The photodiodes output signals were amplified with an adjustable amplifier to get a proper output signal in spite of the differences in light output of the display devices used. For al the devices tested

we determined the absolute luminance level in candela per square meter (cd/m2). For these luminance measurements we used the Milori ColorFacts CF6500. Unfortunately we didn't have the opportunity to determine the absolute luminance level of the Sanyo LCD projector, since this device was tested on location. The data, for this device only, was sampled at 10KHz.

Data analysis

For the statistics we used 100 trials as described above (1, 2, 4 and 8 refresh(es) with a comparable number of refresh(es) black) between them. For the first single frame presentation we computed the relative maximum luminance to verify if the device is able to present single frame pictures. For the full statistics we used the 4 frame presentation, because in the 4 frame event we are sure the device reaches maximum luminance which is important with regard to the rise and the fall time. For these 4 frame events we determined the initial latency, Initial latency screen position differences, rise time, fall time, duration and the relative maximum luminance on each single trial. The initial latency was defined as the time between the sync pulse and the time (in msec) needed to reach 10% of the maximum luminance on the upper left sensor. The initial latency screen position difference was computed by subtracting the initial latency of the upper left sensor from the initial latency of the bottom right sensor. For the rise and fall time we used a more critical approach based on the ISO 13406-2 standard for LCD displays (see figure 1).

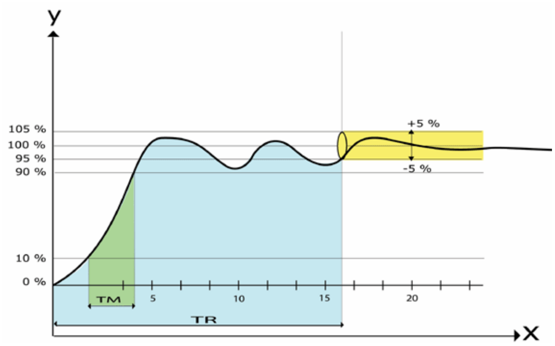

Fig. 1 ISO 13406-2 standard for LCD displays

This ISO standard uses the 10%-90% rule which is common in electronics. So the rise time is defined as the time that passes between 10% and 90% of the maximum luminance on the rising flank. The fall time is defined, as you'd guess, as the time that passes between 90% and 10% of the maximum luminance on the falling flank. Although the time between 0 and 100% is longer, this rule makes sense since the picture is virtually not seen at 10%, and at 90% the picture is a very good approximation of the full illumination. The extremes are especially difficult to pin down accurately, since there is always some variation at the extremes; the maximum and the minimum are not a specific single point stable state. Where some manufacturers allow an extra 5% variation at the maximum illumination, we used the more critical absolute maximum which we used to determine the 10% and 90% illumination level. In practice we found the maximum luminance not to fluctuate that much (5%). The duration of a picture was computed by the time that passes between 10% luminance on the rising flank up to 10% illumination on the

falling flank. For the pulsating light devises we took the total of the duration of each single pulse. For relative maximum luminance we used the peak value reached in the specific condition compared with the peak luminance value found in the whole trial. In the 8 frame presentation al devices easily reached maximum luminance.
For data analysis we also used the VSRRP software which specifies the times, latencies and percentages as specified above on the single trials. For all devices mean values and standard deviation will be reported. For the signal analysis we used the Brain Vision Analyzer software from BrainProducts. The analysis included the following produces; segmentation to single trials based on the synchronization pulse, baseline correction and averaging. The plots presented in this paper will be the averages over the 100 single trials. It should be noted that we did not correct (unlike Wiens et al.) for initial latency differences between trials.
During testing of the LCD panels we noticed that contrast and brightness settings had an eminent effect on the response time of the panel. The more contrast and the brighter the screen was adjusted the faster the response time was.
Furthermore there seem to be some small response time differences between the screens primary colors (red, blue and green). Also changing the screen from the grey shades 80% black to 20% black takes longer than from full white to full black.
Finally there is some evidence that higher color depths (32 bit vs. 16 bit) results in slower response times. For a more detailed explanation of these characteristics we refer to Spaan et al (in press 2005)

Results

CRT

The LG 795Sc has a maximum refresh rate of 120Hz at a resolution of 1024x768. With the default settings the LG 795SC had a maximum luminance level of XXX cd/m2. We used the maximum refresh rate of 120Hz @ 1024x768 for the statistics, which results in a duration of 8.3 msec. for a single refresh.
The CRT device had a mean (and *SD*) relative maximum luminance of 95% (1.28) on the first single frame presentation and 97% (0.86) on the first frame of the 4 frame presentation. For the 4 frame event the mean (and *SD*) initial latency on the upper left sensor was 0.06 msec. (0.02). The initial latency screen position difference was 8.4 msec. (0.02). The mean (and *SD*) rise time was 0.33 msec. (0.02) and the mean (and *SD*) fall time was 0.95 msec. (0.03). The mean (and *SD*) presentation duration for the LG 795SC CRT on the 4 frames event (4 pulses summarized) @ 100Hz (40 msec) was 5.04 msec (0.09)

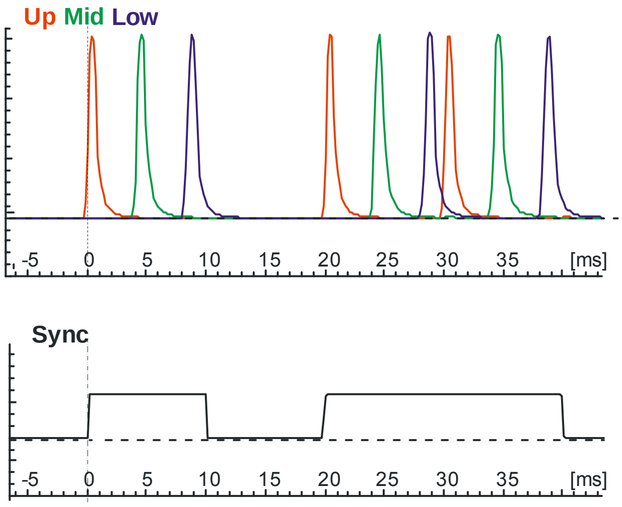

Fig 2 Average luminance for CRT monitor at 100 Hz with single refresh and double refresh display.

LCD panel

The BenQ 767-12 has a maximum refresh rate of 75Hz at a resolution of 1280x1024. With the default settings the BenQ 767-12 had a maximum luminance level of XXX cd/m2. We used the maximum refresh rate of 75Hz @ 1280x1024 for the statistics, which results in a duration of 13.3 msec. for a single refresh.
The LCD device had a mean (and *SD*) relative maximum luminance of 87.71% (0.16) on the first single frame presentation and 99.68% (0.14) on the 4 frame presentation. For the 4 frame event the mean (and *SD*) initial latency on the upper left sensor was 2.80 msec. (0.02). The initial latency screen position difference was 12.21 msec. (0.04). The mean (and *SD*) rise time was 13.83 msec. (0.11) and the mean (and *SD*) fall time was 2.70 msec. (0.02). The mean (and *SD*) presentation duration for the BenQ 767-12 LCD on the 4 frames event @ 75 Hz (53.3 msec) was 53.95 msec. (0.03).

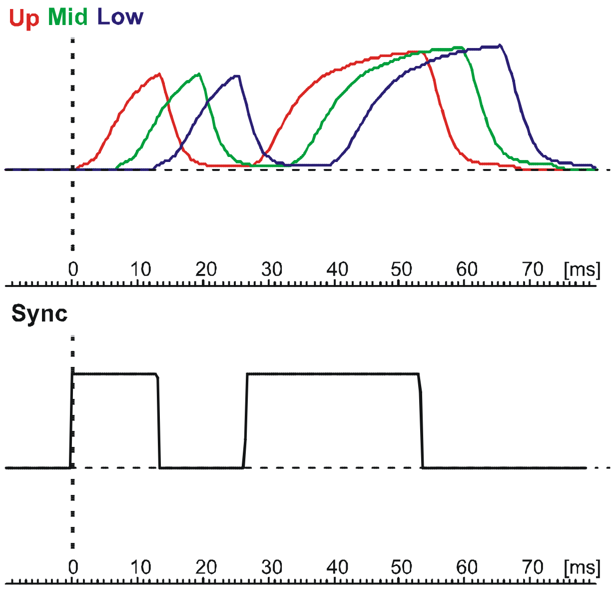

Fig 3 Average luminance for LCD pannel at 75 Hz with single refresh and double refresh display.

LCD projector
The Sanyo PLC-XT16 has a maximum refresh rate of 100Hz at a resolution of 1024x768. During testing we noticed all projectors tested (n=11) had single frame display problems above the 60Hz. At refresh rates higher than 60 Hz refreshes appear not to be synchronized with the screen updates (vertical retrace) calls of the software. This results in partial displays due to refresh operations midway the LCD screen updates. Furthermore the picture is buffered; resulting is a consequent one frame delay. Unfortunately we didn't have the possibility to get the absolute luminance level since we tested this device on location. We used the working refresh rate of 60Hz @ 1024x768 for the statistics which results in a duration of 16.7msec. for a single refresh.
The LCD projector had a mean (and *SD*) relative maximum luminance of 92.58% (2.13) on the first single frame presentation and 99.85% (0.06) on the 4 frame presentation. For the 4 frame event the mean (and *SD*) initial latency on the upper left sensor was 18.16 msec. (0.09), including the 16.7 msec for one frame delay. The initial latency screen position difference was 7.28 msec. (0.13). The mean (and *SD*) rise time was 11.06 msec. (1.40) and the mean (and *SD*) fall time was 3.86 msec. (1.47). The mean (and *SD*) presentation duration for the Sanyo PLC-XT16 projector on the 4 frame @ 60 Hz (66.7 msec) event was 64.63 msec. (0.12).

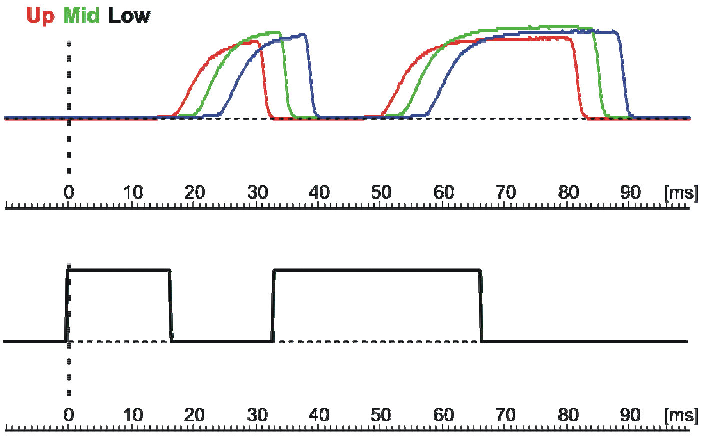

Fig 4 Average luminance LCD projector at 60 Hz with single refresh and double refresh display.

DLP projector
The ProjectionDesign F1 XGA–6 DLP projector has a maximum refresh rate of 120Hz at the 1024x768 resolution. We also noticed single frame display problems above 60Hz on this device. Even at 60 Hz most DLP projectors suffered from synchronization errors. The ProjectionDesign projector however operates flawlessly at 60 Hz. Personal correspondence learned that the firm considers a firmware update enabling the projector to run fully synchronized up to 85 Hz. All the DLP projectors tested (n=6) buffer the picture; resulting in a consequent one frame delay. With the default settings the ProjectionDesign F1 XGA–6 had a maximum luminance level of XXX cd/m2. We used the working refresh rate of 60Hz @ 1024x768 for the statistics which results in a duration of 16.7msec. for a single refresh.

The LCD projector had a mean (and *SD*) relative maximum luminance of 97.97% (0.66) on the first single frame presentation and 99.02% (0.54) on the four frame presentation. For the 4 frame event the mean (and *SD*) initial latency on the upper left sensor was 17.39 msec. (0.03), including the 16.7 msec for one frame delay. The initial latency screen position difference was -0.02 msec. (0.03). The mean (and *SD*) rise time was 0.11 msec. (0.02) and the mean (and *SD*) fall time was 0.23 msec. (0.03). The mean (and *SD*) presentation duration for the ProjectionDesign F1 XGA–6 projector on the 4 frame @ 60 Hz (66.7 msec) event was 22.39 msec. (0.06).

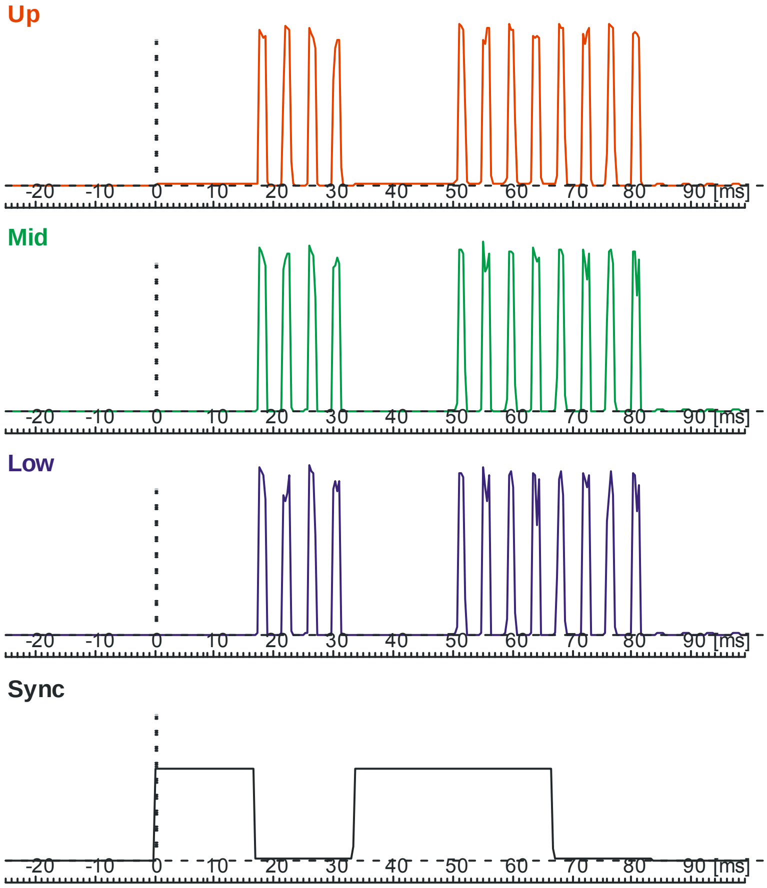

Fig 5 Average luminance DLP projector at 60 Hz with single refresh and double refresh display only red.

Advanced multi projector system (BEAM)

The BEAM system is build with three HITACHI CP-X870 projectors with a maximum refresh rate of 120Hz. The refresh rate is not an issue with regard to the speed of the picture presentation, so we use the projectors at a standard refresh rate of 60 Hz at the 1024x768 resolution. With the default settings the HITACHI CP-X870 had a maximum luminance level of XXX cd/m2 on projector 1, XXX cd/m2 on projector 2 and XXX cd/m2 on projector 3.

The BEAM system works independently of the refresh rate. Instead the BEAM system works with milliseconds. As stated earlier to challenge the BEAM system we did three subsequent short full screen presentations (2, 4 and 8 msec). The BEAM device had a mean (and *SD*) relative maximum luminance of 98% (1.10) on the 2 msec presentation. For the 2 milliseconds event the mean (and *SD*) initial latency on the upper left sensor was 0.02msec. (0.02). The initial latency screen position difference was 0.0 msec. (0.0). The mean (and *SD*) rise time was 0.04 msec. (0.02) and the mean (and *SD*) fall time was 0.08 msec. (0.03). The mean (and *SD*) presentation duration for the BEAM system on the 2 msec event was 2.03 msec. (0.02).

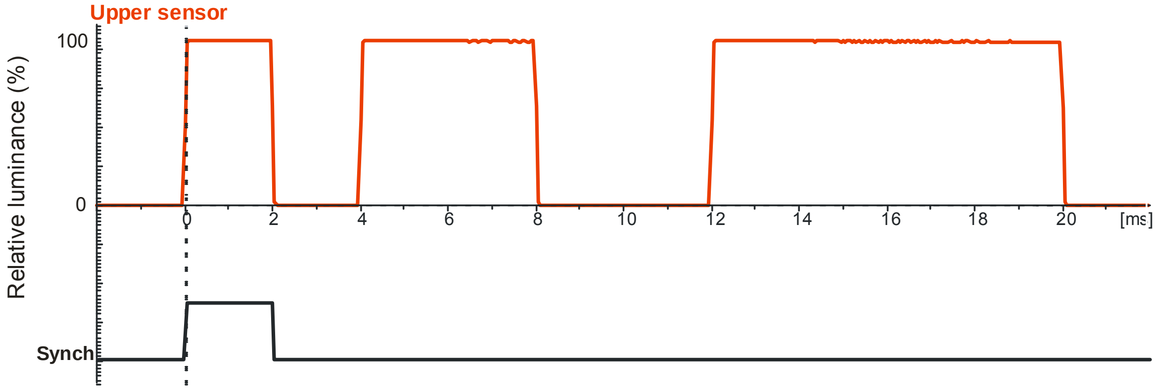

Fig 6 Average luminance of 100 trials for BEAM system with 2, 4 and 8 msec picture presentation.

In short we summarized the results in a Table:

Table 1 The results

	CRT	LCD	LCDproj	DLPproj	BEAM
Cd/m2	140	140	XXX	XXX	XX
Luminance (%) single frame	95% (1.28)	87.71% (0.16)	92.58% (2.13)	97.97% (0.66)	
Luminance (%) four frames	97% (0.86)	99.68% (0.14)	99.85% (0.06)	99.02% (0.54)	98% (1.10)
Initial latency	0.06ms (0.02)	2.80ms (0.02)	18.16ms[1] (0.09)	17.39ms[1] (0.03)	0.02ms (0.02)
initial latency screen position difference	8.4ms (0.02)	12.21ms (0.04)	7.28ms (0.13)	-0.02ms (0.03)	0.0ms (0.0)
Rise time	0.33ms (0.02)	13.83ms (0.11)	11.06ms (1.40)	0.11ms (0.02)	0.04ms (0.02)
Fall time	0.95ms (0.03)	2.70ms (0.02)	3.86ms (1.47)	0.23ms (0.03)	0.08ms (0.03)
Duration 4 frames	40ms	53.3ms	66.7ms	66.7	2.0ms
Measured duration	5.04 (0.09)	53.95ms (0.03)	64.63ms (0.12)	22.39ms[2] (0.06)	2.03ms (0.02)

[1] Please note this value includes the time of one consequent frame delay (=16.7 msec.).

[2] Please note this is the most extreme scenario with only one color displayed (red) resulting in the smallest duration.

Discussion

It is clear by now that there are various possibilities for visual stimuli presentation. Each device has its pro's and cons. Although the CRT plots indicate the screen is most of the time blank, it's apparent that an office employee doesn't have the perception he/she has been watching a blank monitor for 6 of their 8 working hours. As Hunter et al. point out; despite the pulsating picture presentations the CRT monitor is a good replacement of the old cabinet tachistoscope. Researchers ought to be aware of another limitation though. The initial screen buildup is far from ideal, resulting in quite some temporal differences between the upper left corner and the lower right corner. Visual target pictures of different conditions can be best placed on a horizontal line on the screen to avoid timing differences. EEG researchers should time the synchronization pulse so it corresponds to actual stimulus presentation position.

Voorbeeld

With regard to the performance of the LCD panel and the LCD projector we aren't able to endorse the conclusion of Wiens et al. to discourage the use of LCD projectors and panels in studies with brief picture presentations. The study of Wiens et al. does not show the full potential of the present display possibilities due to either outdated equipment data or poor recent equipment selection. Wiens et al. report great variability among trials on all the presentation parameters (duration, initial latency, rise time and relative maximum luminance), and some pictures were not shown at all at the shortest duration (12 ms). Fortunately we did not suffer similar disaster. All the single frame presentations are presented and variance is small. We did however experience problems with LCD projectors at higher refresh rates. Above the 60Hz all the models didn't synchronize correctly with the software, resulting in partial screens. Since Wiens et al. only used one photodiode this may very well explain why they didn't notice this problem. All LCD panels we have tested (n>10) never showed missing frames.
The same recommendations with regard to the initial screen buildup apply to the LCD panel and LCD projector. Compared with the CRT monitor, the LCD panel and projector fall a bit behind on timing resolution. A single frame at 120Hz only takes 8.3 msec where a single frame on the LCD panel takes 13.3 msec and on the LCD projector even takes 16.7 msec. The data show even single frame presentation is very well possible with LCD devices. Although full luminance isn't obtained in the single frame presentation, the picture is a very good approximation of the full illumination. A big advantage of the LCD panel is the non pulsating continuous display.

The DLP projector is also an interesting option for visual stimulus presentation. For now, it has the same 60 Hz (16.7 msec) timing resolution restriction as the LCD projector. This might get better within the near future if the ProjectionDesign projector can handle higher refresh rates. The DLP projector does have a superior initial screen buildup compared with the CRT, LCD panel and LCD projector. However it is not ideal, because a single full RGB picture presentation takes, with the 4 speed color wheel, a bit more than 4 milliseconds. Due to these RGB-RGB-RGB-RGB sequences within one refresh, the continuous display is good but not ideal. Since the picture is buffered it will always be one full frame late. Please take notice of this delay when a synchronization pulse is used. There a small (< 4 msec) difference in onset time of different colors but these small differences ought to be of no concern for most paradigms.

The BEAM system is a true modern computer controlled tachistoscope. A disadvantage is its limited light output. If you can test the subjects in a dim light environment, this system certainly is recommended. The whole picture is literally presented in a flash. Timing resolution and continuous display are excellent. The costs are however rather high. You need three projectors, software and some electronics development to get the system up and running.

It all depends on the paradigms used and the location. For example only LCD panels and projectors can function in an fMRI environment. One should also consider the timing resolution needed. If presentations of 13.3 msec are short enough even the LCD panel will do the job. The ProjectionDesign DLP projector was certainly a pleasant surprise. The DLP display characteristics are good over all. It only suffers a small time resolution at the present 60Hz maximum. We actually preferred this projector for our fMRI display solution. With the ever improving technologies we urge the researchers to take a close look at the devices used. We hope this paper will contribute to awareness of the various possibilities with all their pro's and cons.

Table 2 Overview display possibilities and disabilities

Devices	Initial screen buildup	Rise and fall time Duration	Continuous display	Brightness	time resolution
CRT	-	++	--	+	+
LCD pannel	-	+/-	++	+	+/-
LCD projector	-	+/-	++	++	-
DLP projector	+	+	+	++	-
BEAM system	++	++	++	--	++

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