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Multiple serial picture presentation with millisecond resolution using a three-way LC-shutter-tachistoscope

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ABSTRACT

Throughout recent years there has been an increasing interest in studying unconscious visual processes. Such conditions of unawareness are typically achieved by either a sufficient reduction of the stimulus presentation time or visual masking. However, there are growing concerns about the reliability of the presentation devices used. As all these devices show great variability in presentation parameters, the processing of visual stimuli becomes dependent on the display-device, e.g. minimal changes in the physical stimulus properties may have an enormous impact on stimulus processing by the sensory system and on the actual experience of the stimulus.

Here we present a custom-built three-way LC-shutter-tachistoscope which allows experimental setups with both, precise and reliable stimulus delivery, and millisecond resolution. This tachistoscope consists of three LCD-projectors equipped with zoom lenses to enable stimulus presentation via a built-in mirror-system onto a back projection screen from an adjacent room. Two high-speed liquid crystal shutters are mounted serially in front of each projector to control the stimulus duration. To verify the intended properties empirically, different sequences of presentation times were performed while changes in optical power were measured using a photoreceiver.

The obtained results demonstrate that interfering variabilities in stimulus parameters and stimulus rendering are markedly reduced. Together with the possibility to collect external signals and to send trigger-signals to other devices, this tachistoscope represents a highly flexible and easy to set up research tool not only for the study of unconscious processing in the brain but for vision research in general.

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1. Introduction

While the study of implicit (unconscious) visual perception has a century-long and controversial history (for a review see Kouider and Dehaene, 2007), interest in neuroimaging studies of perception without awareness has started only recently. Neuronal processes associated with implicit perception are generally inferred from contrasts between conditions of unawareness and conscious perception. Central for most studies in this area is the idea that a reduction of conscious awareness, achieved either by reduced stimulus presentation time or visual masking (Enns and Di Lollo, 2000; Kim and Blake, 2005), goes along with less conscious stimulus processing. Stimulus design and stimulus presentation, therefore, represent the most crucial part of an experiment, and great care needs to be taken to ensure stimulus presentation quality, in particular stimulus duration.

In a typical experiment, stimuli are presented using either a cathode-ray tube (CRT), a liquid crystal display (LCD), or a thin-film transistor (TFT) monitor or projector. The actual processing of visual stimuli, however, critically depends on the display-device employed. CRT monitors, for example, permit excellent timing due to CRT-internal refresh rates, but stimuli are reproduced with low reliability in space, luminance, and colour (Krantz, 2000). On the other side, LCD/TFT monitors or projectors present images in steady state, thus representing a more valid method for stimulus delivery. However, neither picture onset nor duration can be controlled exactly with these devices.

In general, all standard presentation devices show great variability in stimulus latency, onset, luminance, and duration across trials. This variability is even increased when pictures are presented very briefly (Wiens et al., 2004). At first sight, such variability in stimulus parameters seem to pose no problem, since individual conditions

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are repeated several times and thus variability in stimulus parameters is often thought to simply "average out". Yet, research suggests that minimal changes in the physical stimulus properties may have an enormous impact on stimulus processing by the sensory system and therefore on the actual experience of the stimulus (Esteves and Öhman, 1993). Additionally, presentation parameters become dependent on each other with brief presentation times, e.g. manipulation of stimulus duration also affects overall luminance (Wiens et al., 2004). Thus, experimental results are confounded by duration as well as overall luminance changes and, therefore, conditions involving unequal stimulus durations (i.e. different levels of awareness) cannot be compared directly. Furthermore, efforts to establish and assess objective thresholds for awareness for single subjects are impaired since such approaches (e.g. signal detection methods) require multiple trials with constant and reliable presentation parameter to show that observers actually perform no better than chance (Hannula et al., 2005). Finally, unwanted variability in stimulus parameters induces "noise" in the data, leading to an increased type II error and, therefore, subtle differences across conditions may not be detected.

Clearly, these are crucial theoretical and methodical issues that have to be considered (Erdelyi, 2004; Hannula et al., 2005; Wiens and Öhman, 2007; Kouider and Dehaene, 2007) when investigating implicit (unconscious) visual perception involving very brief stimuli (e.g., below a supposed threshold of awareness). However, the afore mentioned issues not just apply to tachistoscopic presented stimuli, but to all experiments where stimulus presentation is repeated with the necessity of identical physical parameters, e.g. rapid serial visual presentation protocols (RSVP). Therefore, novel techniques are required to achieve well-defined and controlled stimulus delivery to overcome these shortcomings.

Several technical approaches have been proposed in the literature, however, exact parameters for the stimulus delivery are either not available or hard to verify. Some devices also fall short in one dimension (e.g. control of luminance), or lack flexibility in stimulus parameter ranges (e.g. with CRT monitors only in multiples of their refresh-rate, like 16 ms, 32 ms, etc.). Compatibility with the MR-environment is another critical issue, as some presentation systems are optimised for CRT monitors (MacInnes and Taylor, 2001; Tsai, 2001; Fiesta and Eagleman, 2008) which however cannot be used in functional MRI studies because they interfere with the imaging process.

Here we present an approach for visual stimulus delivery that is aimed at surmounting these shortcomings, e.g. that allows well-defined stimulus timing in the millisecond range, homogeneous stimulus brightness, and high stimulus reproducibility. The device is based on three separate LCD-projectors equipped with shutters that are combined to form a so-called tachistoscope, first described by Volkmann in 1859. This first tachistoscope consisted of a movable metal plate with an opening that corresponded to the size of an image placed on a table. This metal plate was fixated by a handle and attached to a weight hanging over the edge of the table. By releasing this handle, the plate quickly moved over the table pulled along by the weight and the previously hidden image under the plate became briefly visible to an observer standing in front of the table. Since then various solutions were proposed, e.g. so-called gravity chronometers allowing for a much tighter control of the stimulus presentation duration (for a review see Benschop, 1998). Modern devices consist of two slide projectors with mechanical shutters attached to their lenses (Esteves and Öhman, 1993). However, careful analysis of available tachistoscopes (Mollon and Polden, 1978) and recent measurements by Wiens et al. (2004) showed that most devices offered poorer presentation parameters than assumed or claimed by the manufacturer.

In order to use the tachistoscope for our current experiments it was necessary to develop a three-way LC-shutter-tachistoscope with a dedicated programming language to adequately control stimulus generation and shutter switching sequences. These experiments involve the rapid presentation of images below the subjects' individual visual threshold, e.g. below 10 ms. Such designs cannot be accomplished with only two LCD-projectors since the refresh-rate of the projector (72 Hz in our case) is too long to guaranteed steady-state image production, i.e. the presentation duration of one image is shorter than the time needed to update the image of the other, not presenting projector. However, for most other experiments in the domain of vision research two or even one projector might be sufficient. Thus, we will also show how such a tachistoscope can be set up by providing the connection scheme and driving methodology for a single projector system. Since the LC-shutter-tachistoscope follows a modular concept, this logic can be used to set up any system, based on one's own needs.

The performance of the tachistoscope with a particular focus on stimulus reproducibility was assessed using a photodiode setup according the recent recommendation by Wiens and Öhman (2005).

2. Methods and materials

2.1. Apparatus

The device described herein consists of three components: (1) the projection-unit, (2) a shutter-control-device (SCD), and (3) a control PC.

The projection-unit (developed and assembled by K. Zickler G.m.b.H., Paffstätten, Austria) consists of three EMP-7900 LCD-projectors (Epson America, Inc., Long Beach, CA, USA) mounted on top of each other in horizontal position. Each projector is equipped with a long-focus NuView 606 MCZ087 zoom lens (Navitar Presentation Products, Rochester, NY, USA) allowing for distances of several meters between the tachistoscope and the small-sized projection screen, as required for fMRI-applications when presenting from an adjacent room.

Single projector light paths are collected and joined to a single light-output via a mirror-system to enable stimulus presentation through a single waveguide when used in a fMRI environment (Fig. 1). As an additional benefit this setup avoids trapezoidal distortions which would occur with direct single projector light paths due to different projection angles. The mirror-system consists of four achromatic mirrors (Prinz Optics G.m.b.H., Stromberg, Germany) that are adjustable in angle. The bottom and top mirror are "simple" mirrors, while the two mirrors in between have semireflecting properties, splitting the light beam at a translucence/reflection ratio of 0.5 : 0.5 and 0.7 : 0.3, respectively. While the specific features of the mirrors used already ensure similar luminance from all three light paths, brightness can additionally be adjusted individually for each path via the projector-control device.

The actual presentation timing is accomplished by FOS-25x30-PSCT high-speed liquid crystal optical-shutters (LC-Tec Displays AB, Borlänge, Sweden) with an active display area of 21 mm×21 mm. LC-shutters were favoured since they combine high transmittance (according to the manufacturer $T > 86\%$ in transparent state) together with fast switching speeds without any noise. Furthermore, they provide more natural viewing conditions than mechanical shutters, e.g. transitions from light-scattering to transparent mode and vice versa occur homogeneously across the whole picture, which avoids unwanted pinhole-effects as well as opening or closing bounces. Two such shutters are serially mounted in front of each lens to ensure complete blackout when in light-scattering state (Fig. 1). Pilot test with only one shutter per lens showed residual light-transmittance of about 2% during dynamic switching, which did not lead to non-zero visibility of presented stimuli when shutters were closed.

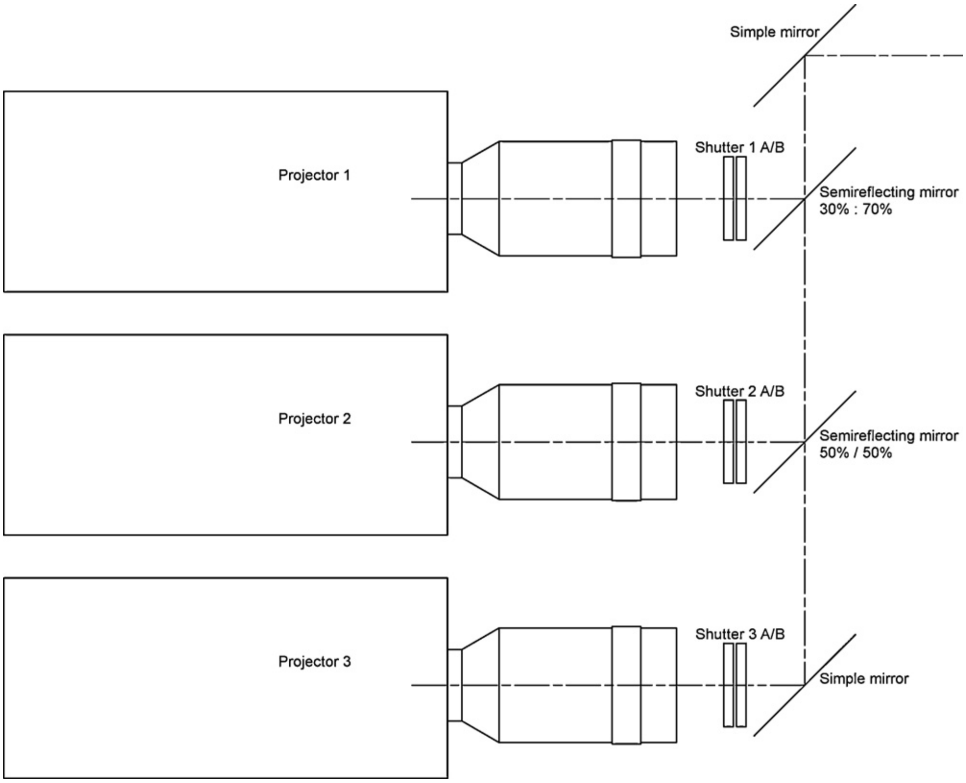

Fig. 1. Schematic overview of the projection-unit of the tachistoscope. It consists of three LCD-projectors – each equipped with a long focal length zoom lens, rack-mounted on top of each other – and the mirror-tower. The mirrors collect the different light paths via semireflecting mirrors to form one single light-output. Stimulus delivery is provided by two high-speed liquid crystal optical-shutters (A and B) serially mounted in front of each lens. (c.f. text for further details).

The shutters are controlled by the shutter-control-device (developed by K. Zickler G.m.b.H., Pfaffstätten, Austria), which offers two independent operating modes, “*external-mode*” and “*program-mode*”. In “*external-mode*” changes of shutter states may be triggered either manually via toggle switches, or by a 5 V TTL-pulse through three built-in ports, one for each light path. Such TTL-pulses can be generated by almost any commercially available presentation software via a PC parallel IO-port, thus allowing for easy integration of the tachistoscope in any already existing environment without additional software demands.

In “*program-mode*” a sequence of shutter operating commands is preloaded into a SC13-LF 40 MHz microprocessor (Beck IPC G.m.b.H., Pohlheim-Garbenteich, Germany) and then executed. In this mode much faster event sequences may be realised, and tighter control as well as higher flexibility of the experimental design is possible. Programming of this built-in microprocessor was done with a real-time multi-tasking Operating System (RTOS) which allows to collect external signals during execution (e.g. fMRI-pulses, subject-responses) and to send triggers to an external device by means of TTL-pulses. These signals can either be used to control certain aspects of the experimental paradigm or as synchronisation signals for external data-acquisition devices.

A 1 kHz square-wave duty-cycle serves as the SCD-internal clock to synchronise events in both modes. That means, whenever a change in shutter state is requested this event will be synchronised to the next rising edge of the clock signal allowing for reliable and precise stimulus delivery in steps of 1 ms. This principal is realised in each of the three shutter-projector units but driven by one and the same SCD-internal clock to ensure synchronisation of all three shutter-projector units. This way, high flexibility in experimental designs is provided, since continuous presentation of various images is possible with images built up in the background, by sequential activation of different shutter-projector units.

The actual change in shutter state is accomplished by applying two asynchronous square-wave signals with 140 V effective voltage at a frequency of 1 kHz to the two input channels of a single LC-shutter initiating the transparent state. As plotted in Fig. 2, rows 3 and 4, channel 1 is in a high-voltage state, whenever channel 2 receives no voltage input and vice versa. This continuous polarity switching of the DC voltage at the two input channels allows (1) minimal rise times, (2) fast and repeated switching and insures (3) increased life-time and stability of these LC-shutters (for more details see http://www.lctecdisplays.com/FOS-PSCT.asp). Withdrawing the driving voltage immediately initiates the light-scattering mode. The two serially mounted shutters per projection-unit are electrically driven in parallel mode. Time-point of the state changes are logged by the microprocessor and additionally signalled by means of TTL-pulses, via separate outputs one port per projection-unit. These TTL-pulses in turn can be used for logging purposes, e.g. when operating in “*external-mode*”. The driving sequence for a single 3 ms event on a single shutter-projector unit is illustrated in Fig. 2. In Fig. 3 the corresponding block diagram of the driving-circuit for a single shutter-projector unit is given.

To operate the SCD in “*program-mode*” a control software has been developed to control (1) the stimulus presentation and (2) to run the whole experiment. This control software also maintain an Ethernet connection between the presentation PC and the SCD. Via this connection shutter release sequences are sent to the SCD and signals from external devices and log-files are collected from the SCD. This software is based on the Qt4 development environment (http://www.qtsoftware.com/) and runs on a conventional Linux computer equipped with 2 dual-port graphic cards. Image generation is realised independently on each of the four available graphic ports in “OpenGL” as implemented in Qt4 via the X-Windows standard. “OpenGL” is a hardware-independent high-performance graphics library that allows for direct rendering to the

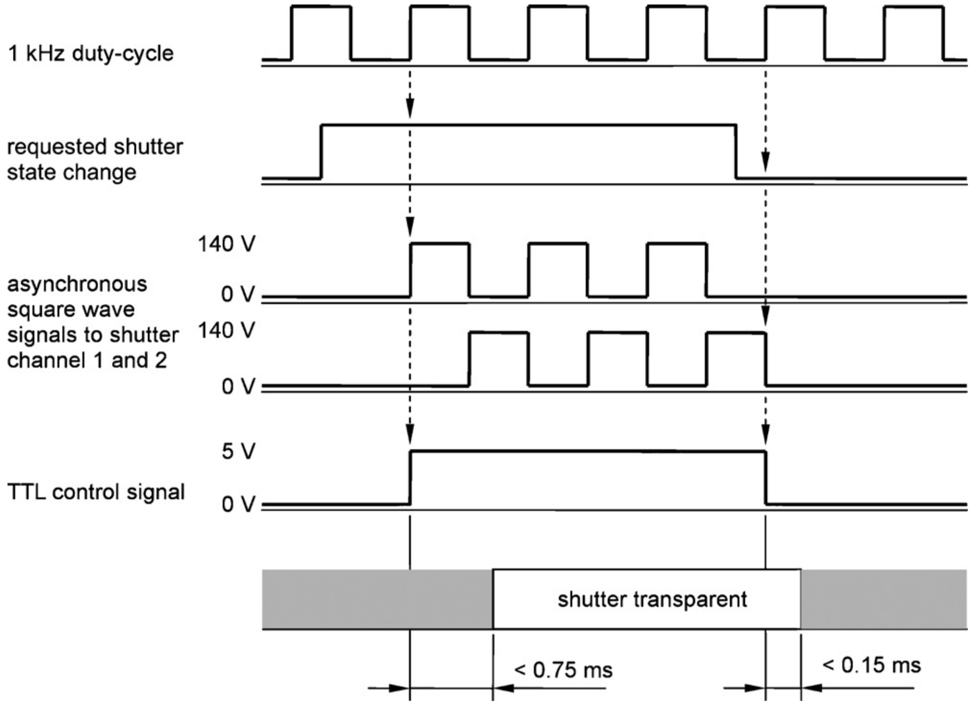

Fig. 2. Control principle for a single shutter to present a 3 ms stimulus. The 1 kHz square-wave duty-cycle shown in the first row serves as an internal clock to synchronise events. Requested shutter state changes (second row) are synchronised with the next rising edge of this clock (first row), signalled via a TTL signal (fifth row), and are finally accomplished by applying two asynchronous square-wave signal with 140 V effective voltage to the shutter inputs (row 3 and 4). The last row shows the actual switching of the shutters as measured with a photoreceiver. (c.f. text for further details and Fig. 3 for the connection scheme to realise this mechanism).

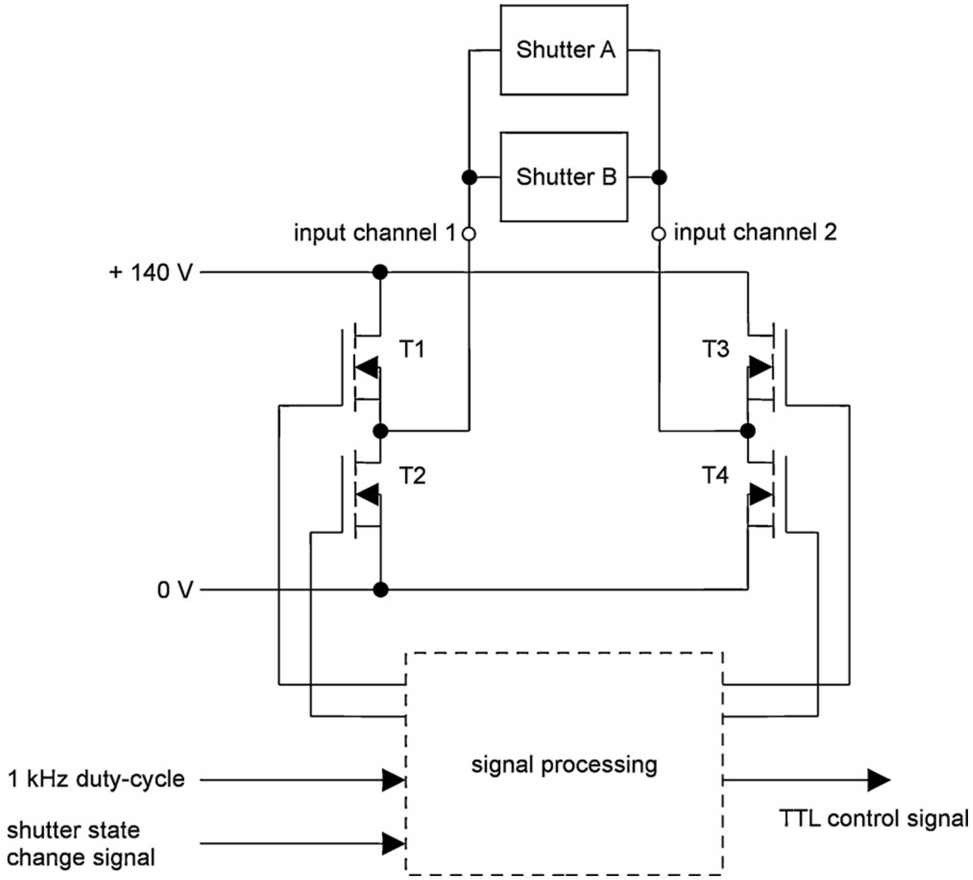

Fig. 3. Connection scheme that illustrates the set up and control of a single shutter-projector unit. To initiate the transparent state of the shutter a 1 kHz polarity switching voltage signal of 140 V is applied to its two input channels (c.f. also Fig. 2 rows 3 and 4). This mechanism is accomplished by activating corresponding pairs of switching transistor (metal-oxide semiconductor field-effect transistor: T1–4), i.e. whenever T1 and T4 is switched on, positive voltage is applied to shutter input channel 1 and negative voltage to channel 2 and vice versa. The signals used to trigger the transistors are generated by the signal processing unit by simply synchronising the shutter state change signal to the 1 kHz square-wave duty-cycle. Removal of this voltage permits the rapid relaxation of the shutters to light-scattering mode (c.f. text for further details).

video card while providing millisecond accuracy (Stewart, 2006). This way, images can be presented and changed independently for each projector at any time throughout the experiment.

In addition, this software provides a shutter-item-programming language (SIPL) in order to describe the whole experiment in a single script. Such scripts can be executed and supervised via a graphical user-interface. The basic structure of such scripts comprises “*l* ocal” and “*remote*” elements. These elements are grouped to form the item sequence of an experiment and are serially, i.e. on an item per item basis executed.

“*Local*” elements are executed on the presentation computer and are used to define (among others) the images to be presented, their location on the screen, and the projector to be used. “*Remote*” elements hold the exact description of the shutter release sequence, i.e. which shutter is to be activated for how long and when, e.g. following an external trigger. The “*remote*” elements are sent to the SCD after all “*local*” elements of this item have been executed. Thus, the fact that projectors require some time to build up stable images is accounted for, and shutter release will not started before the projector display is in steady-state.

In the following, the script for the performance and accuracy tests as described in the next section will be illustrated. This script consists of only one item holding one “*local*” and one “*r* emote” element. By the “*local*” element the filename of the image to be presented (here a simple white bitmap), its position and size on the screen (centred and scaled to fullscreen), and the projector number to be used (projector three for this experiment) are specified. The “*remote*” element contain for projector three a sequence of “ons”, of various durations, and “offs”, of a duration of 50 ms, repeated 500 times altogether, while for projector one and two, the “*remote*” elements are empty.

2.2. Test procedure and data analysis

Performance and accuracy of the tachistoscope were assessed using photodiode-measurements. To this end a 200 kHz Si Photoreceiver Model 2001-FC (New Focus Inc., San Jose, CA, USA) was placed in the centre of the mirror-tower’s light-output. The photoreceiver contained a Silicon-based photodiode with a light-sensitive area of 0.81 mm^2 and a very short rise time (2 μs). This photoreceiver was connected to a transimpedance amplifier allowing to measure optical input power. Optical power that strikes the photodetector is equal to the voltage measured divided by the wavelength response factor. This calibration factor was set to 0.25, which approximately specifies visible light. Together with a marker signal from the TTL-port of the SCD both signals were recorded with 50 kHz sampling frequency using a ME-2600 12-bit multiport ADC-card (Meilhaus Electronic G.m.b.H., Puchheim bei München, Germany).

For these test measurements the tachistoscope was operated in “*p* rogram-mode”, and the stimulus was a white bitmap across the entire screen continuously presented by the undermost projector at a resolution of 1024 × 768 pixels (32-bit colour). As such, the light had to pass all mirrors before reaching the photodiode. Light intensity changes were measured for eleven presentation durations (1–10, and 15 ms), and each presentation was repeated 500 times with an inter-stimulus-interval of 50 ms. Additionally, two 5-min baseline runs were conducted, one with all shutters closed and one while shutters were open. These runs were used to describe possible luminance fluctuations induced by shutters and/or projectors. All measurements were performed at room temperature in a darkened surrounding to avoid adventitious light and diffuse reflections from outside.

From these data the following five parameters were derived separately for each target-duration: initial latency, rise-time, fall-time, observed duration, and relative maximum brightness. Moreover, as operational parameters, the mean and the standard deviation over time for the two long-term runs were calculated to defined a baseline while shutters were closed and the absolute maximum light power when shutters were open. All these calculations were performed on the raw signal, i.e. without baseline-correction, smoothing, or filtering.

The initial latency was defined as the interval (in milliseconds) between the onset of the marker signal and the stimulus onset, given as the time-point when the optical power exceeded 10% of its maximum level. Relative maximum optical power was defined as the percentage of the maximum brightness obtained in the long-term run. The power level was calculated as the mean light power above the 90% level of maximum brightness.

The rise-time was, according to Wiens et al. (2004), defined as the mean interval (in milliseconds) between stimulus onset and the half-maximum of the rising edge of the measured waveform, and the fall time as the interval between the half-maximum of the falling edge and stimulus offset, when the brightness fell below 10% of its maximum. Finally, the observed duration was computed via the full width at half-maximum (FWHM) given by the temporal difference (in milliseconds) between the two values, at which the recorded optical power was equal to half of its maximum value.

3. Results

Measurement results from the two baseline runs showed almost perfect blacking-out by the two serial shutters resulting in a residual transmittance of 0.0028%. With all shutters open we found mean light power of 0.0274 mW (SD 0.0066), while the residual power averaged to 7.5744×10^{-05} mW (SD 9.7665×10^{-05}) when shutters were closed.

Fig. 4B depicts the mean power curve for a run of 5 ms presentations. The optical power at this stimulus duration was found to be constant and stable across single trials. This is illustrated by the standard deviation plotted every tenth time-point showing an exact and reliable stimulus delivery across the 500 repetitions with this brief stimulus duration. The increase in standard deviation over time following the opening of the shutters is caused by the projector light-source which causes a 192 Hz background flickering. This

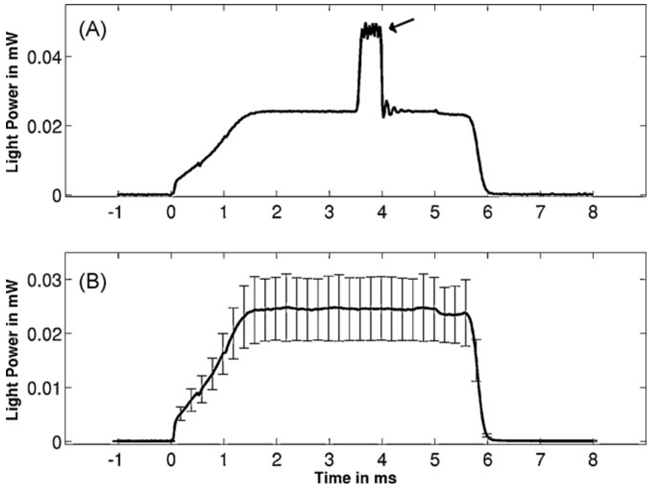

Fig. 4. Optical power curve over time for a single stimulus with a target-duration of 5 ms (A) and mean and standard deviation (plotted at every tenth time-point) of optical power across the 500 repetitions with this brief stimulus duration (B). Please note, the exact and reliable stimulus delivery at this brief target-duration. No baseline-correction, data-smoothing, or filtering was performed on the data. The increase in standard deviation following the opening of the shutters is due to short light pulses (arrow in A) caused by the light-source of the projector at a frequency of a 192 Hz (c.f. text for more details).

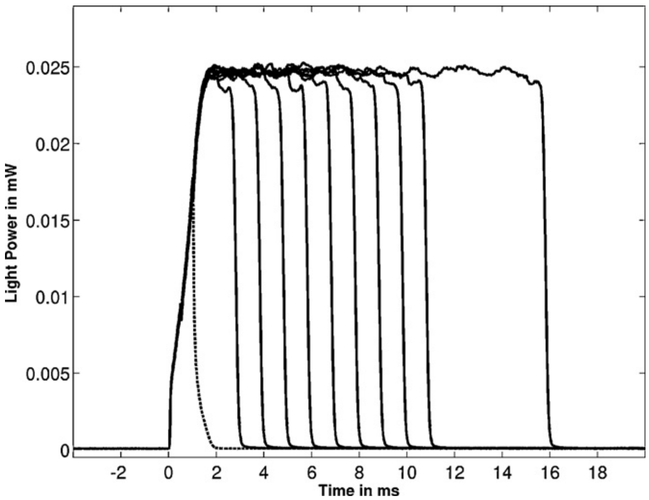

Fig. 5. Onset locked mean optical power curves for presentation times varying from 1 ms to 10 ms in steps of 1 ms and 15 ms. After a common onset the individual waveforms stay at a constant level before showing a steplike offset at the desired stimulus end. Only with the duration of 1 ms (dotted line), the stimulus fails to reach its maximum optical power. Note that the data were not preprocessed in any way before being graphed.

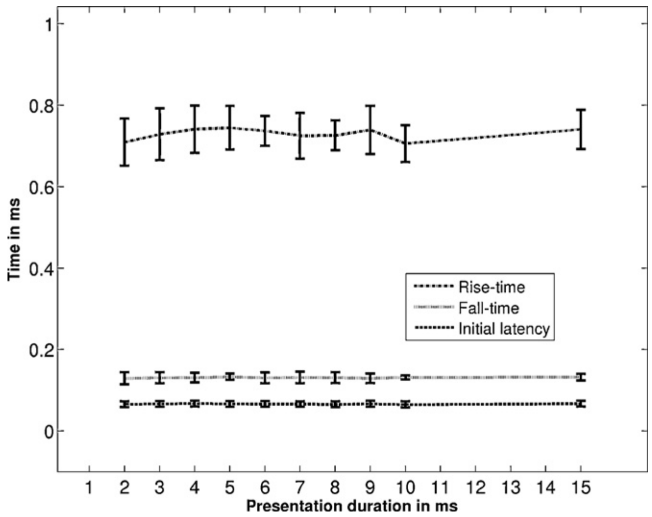

Fig. 6. Mean rise-time (top line), fall-time (middle line), and initial latency (bottom line) with their standard deviations of the eleven presentation durations (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 15 ms). Detailed results are summarised in Table 1.

variability, also found by Wiens et al. (2004), is also visible in the long-term run where shutters were constantly open as well. However, this pulse are rather short (mean FWHM 0.442 ms) as can be seen in Fig. 4A at around 3.5 ms for a single 5 ms stimulus.

Mean light power curves for all target-duration runs are shown in Fig. 5. Note that only at the 1 ms condition the stimulus failed to reach its maximum and therefore, this condition was removed from further analysis. With all other stimulus durations the relative maximum light power never fell below 95.75% of the maximum brightness as measured in the long-term run (see Table 1). As illustrated in Fig. 5, little variability is observable in initial latency, rise-time, and maximum relative optical power. Moreover, individual waveforms show a steplike offset at the desired stimulus offset. Note for both Figs. 4 and 5, that the data were not corrected in any way before being plotted.

Across all sequences the initial latency was found to be 0.066 ± 0.007 ms (mean ± SD) and showed only little variability with the different stimulus durations. The same is true for the rise-time: 0.7298 ± 0.0538 ms and the fall-time: 0.1309 ± 0.0118 ms. The nominal and the actual presentation duration show extremely high linear correlation ($\rho = 0.999881$) with a mean difference of 0.0088 ± 0.0097 ms. Detailed results for the different stimulus durations are listed in Table 1 and presented in Figs. 6 and 7.

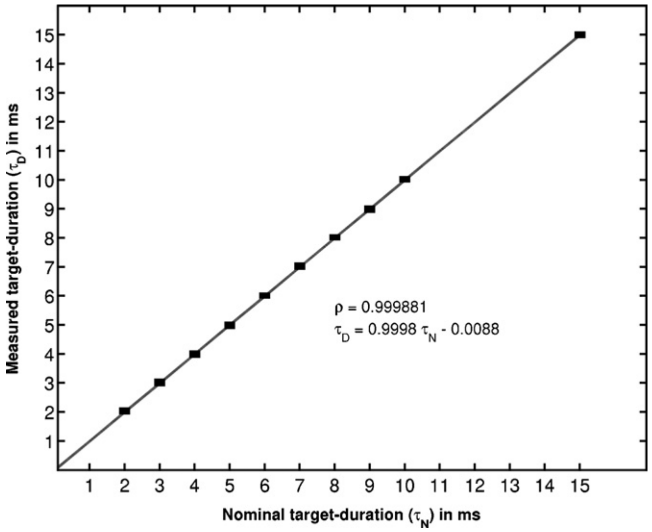

Fig. 7. Mean and standard deviation of observed target-presentation durations for the eleven presentation durations (1, 2, 3, 4, 5, 6, 7, 8, 9, 10, and 15 ms). Additionally, the regression line with the given parameters is plotted. Detailed results are given in Table 1.

Table 1
Detailed results for the five derived parameters broken down for the different stimulus durations. Columns give the nominal stimulus duration (first column), the initial latency, the rise-time, the fall-time, and the actually measured duration in ms. The last column shows the mean relative maximum brightness at the given stimulus duration as a percentage of the maximum optical power derived during the long-term run (c.f. text for further details).

Nominal duration	Initial latency	Rise-time	Fall-time	Actual duration	Relative brightness
2 ms	0.0656 ms (0.0069)	0.7093 ms (0.0578)	0.1292 ms (0.0146)	2.0348 ms (0.0580)	0.9575
3 ms	0.0664 ms (0.0072)	0.7287 ms (0.0638)	0.1305 ms (0.0133)	3.0121 ms (0.0654)	1.0236
4 ms	0.0671 ms (0.0069)	0.7415 ms (0.0581)	0.1309 ms (0.0115)	3.9947 ms (0.0604)	1.0439
5 ms	0.0664 ms (0.0069)	0.7445 ms (0.0538)	0.1332 ms (0.0080)	4.9862 ms (0.0629)	1.0654
6 ms	0.0662 ms (0.0069)	0.7370 ms (0.0369)	0.1303 ms (0.0132)	6.0093 ms (0.0408)	1.0349
7 ms	0.0661 ms (0.0068)	0.7250 ms (0.0563)	0.1310 ms (0.0144)	7.0218 ms (0.0580)	1.0000
8 ms	0.0655 ms (0.0069)	0.7258 ms (0.0365)	0.1308 ms (0.0133)	8.0198 ms (0.0398)	0.9823
9 ms	0.0664 ms (0.0074)	0.7394 ms (0.0591)	0.1293 ms (0.0115)	8.9920 ms (0.0604)	0.9795
10 ms	0.0650 ms (0.0072)	0.7059 ms (0.0451)	0.1315 ms (0.0050)	10.0192 ms (0.0437)	0.9714
15 ms	0.0669 ms (0.0072)	0.7407 ms (0.0480)	0.1324 ms (0.0082)	14.9980 ms (0.0481)	0.9618
mean	0.0662 ms (0.0071)	0.7298 ms (0.0538)	0.1309 ms (0.0118)	–	1.0020

Note: For the computation of these parameters the raw-signal was taken as measured, i.e. without baseline-correction, data-smoothing, or filtering.

As is apparent in Fig. 4 A and B as well as in Fig. 5 shutters did not show any opening or closing bounces. The small fluctuations in the maximum brightness common to all presentation durations are due to the projector light-source as mentioned above (c.f. also Fig. 4A). The two small dips, one around 0.5 ms after onset and one directly prior to signal-offset, originated from the LC-shutter switching. While the first dip results from the switching between the two square-wave driving voltages, the second can be explained by the technical properties of the shutters; according to the manufacturer, this shutter-type remains transparent for a certain holding-time prior to relaxing to light-scattering state after the voltage has been removed. This holding-time is a function of temperature and capacity of the shutters and was always less than 0.5 ms throughout all runs.

4. Discussion

Studies on implicit or unconscious visual processing are typically based on the comparison of conditions without awareness and conditions involving conscious stimulus processing. As already mentioned, unconscious conditions are achieved by either a sufficient reduction of the stimulus presentation time or visual masking. With both approaches, accurate stimulus timing is essential in order to prevent conscious processing. Although there is general agreement about the theoretical and methodical issues that have to be met (c.f. Hannula et al., 2005; Wiens and Öhman, 2007), there are growing concerns currently noticeable about the reliability of the presentation devices used in such designs (e.g. Krantz, 2000; Wiens, 2006).

In a recent study, Wiens et al. (2004) compared presentation parameters of several commonly used stimulus presentation methods and found poor accuracy particularly with short stimulus durations, e.g. the average difference between desired and observed stimulus duration turned out to be 3.7 ms for mechanical shutters, 6.2 ms for LCD data projectors and 49.2 ms for the thin-film transistor panels. Additionally, Wiens and colleagues were able to demonstrates that presentation durations below 47 ms are not possible with the tested LCD-projector or TFT panel due to their inherently long rise-times. In contrast, cathode-ray tube monitors exhibited minimal variability across trials and target-duration thus providing excellent timing. However, the overall brightness levels tended to decrease with shorter stimulus durations as shown at two refresh rates: 60 and 85 Hz with a lower brightness level at 85 Hz.

These results would clearly favour the use of CRT monitors. Yet, these devices are not compatible with the MR-environment and lack flexibility in stimulus parameter range, e.g. one is restricted to a given set of stimulus durations unless one dynamically changes the refresh rates during the experiment. Such an approach was recently described by Fiesta and Eagleman (2008) allowing to adjust the refresh-rate of CRTs on a trial to trial basis. While this approach allows to achieve a wide range of presentation durations of 16.7–120 ms, the overall brightness levels may still differ at various refresh rates (Wiens et al., 2004). Finally, CRT-monitors are about to disappear from the market and if still available are difficult to handle due to missing display-drivers and appropriate routines.

The purpose of this study was to develop a tachistoscope capable of presenting stimuli with well-defined properties at a millisecond temporal resolution. The setup involves three LCD-projectors, each equipped with a special zoom lens to enable stimulus presentation via a built-in mirror-system onto a back projection screen. Two high-speed liquid crystal shutters were serially mounted in front of each projector to control the stimulus presentation time. In contrast to previously favoured mechanical shutters (e.g. Esteves and Öhman, 1993; Wiens and Öhman, 2005), the liquid crystal LC-shutters were favoured for this tachistoscope since they provide rather natural viewing conditions since they do not show any opening or closing bounces or pinhole-effects. Optical-shutters further allow for short and highly repeated stimulus presentation with durations as low as 2 ms while mechanical shutters are limited to a lower stimulus duration of roughly 8 ms, depending on the manufacturer. Finally, these shutters are noiselessness. Although irrelevant for MRI, this feature makes them perfectly suited for regular labs e.g. running behavioural or EEG experiment.

In order to verify the intended properties empirically, brightness changes were measured using a photoreceiver placed into the light path while different sequences of presentation times in steps of 1 ms were performed. The results clearly demonstrate that the variability of the stimulus presentation duration is markedly reduced compared to previously described methods (Mollon and Polden, 1978; Wiens et al., 2004). The overall light power level was found to be highly reproducible across stimulus durations of 2–15 ms; only 1 ms stimuli failed to reach maximum brightness.

In summary, the presented approach for a three-way LC-shutter-tachistoscope enables for the first time experimental setups with both precise stimulus delivery and millisecond resolution (minimum stimulus length: 2 ms, minimum inter-stimulus delay: 1 ms). Interfering variability in stimulus parameters and stimulus rendering associated with digital projectors or computer monitors are thereby strongly reduced. In conjunction with the use of multiple LCD-projectors this setup engages stable, steady-state image production before shutter release, allowing for almost natural viewing conditions. Together with the feature to collect external signals (e.g. fMRI-pulses, subject-responses) and to send trigger-signals to external devices, it represents a highly flexible and easy to set up research tool not only for the study of unconscious processing in the brain but for vision research in general.

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