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Ultrahigh temporal resolution of visual presentation using gaming monitors and G-Sync

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Abstract

Vision unfolds as an intricate pattern of information processing over time. Studying vision and visual cognition therefore requires precise manipulations of the timing of visual stimulus presentation. Although standard computer display technologies offer great accuracy and precision of visual presentation, their temporal resolution is limited. This limitation stems from the fact that the presentation of rendered stimuli has to wait until the next refresh of the computer screen. We present a novel method for presenting visual stimuli with ultrahigh temporal resolution (<1 ms) on newly available gaming monitors. The method capitalizes on the G-Sync technology, which allows for presenting stimuli as soon as they have been rendered by the computer's graphics card, without having to wait for the next screen refresh. We provide software implementations in the three programming languages C++, Python (using PsychoPy2), and Matlab (using Psychtoolbox3). For all implementations, we confirmed the ultrahigh temporal resolution of visual presentation with external measurements by using a photodiode. Moreover, a psychophysical experiment revealed that the ultrahigh temporal resolution impacts on human visual performance. Specifically, observers' object recognition performance improved over fine-grained increases of object presentation duration in a theoretically predicted way. Taken together, the present study shows that the G-Sync-based presentation method enables researchers to investigate visual processes whose data patterns were concealed by the low temporal resolution of previous technologies. Therefore, this new presentation method may be a valuable tool for experimental psychologists and neuroscientists studying vision and its temporal characteristics.

Keywords Display · Screen · CRT replacement · Vision · Visual cognition · Psychophysics

Vision is an intricate pattern of information processing over time. Studying vision and visual cognition therefore requires precise control over the timing of visual stimulus presentation. This requirement is most clearly illustrated by studies dating back to the beginnings of experimental psychology in the 19th century (Cattell, 1885, 1886). These studies built upon the development of new apparatuses for presenting visual stimuli briefly and in a highly controlled fashion (for reviews, see Bauer, 2015; Benschop, 1998). More specifically, brief stimulus presentation with these apparatuses for the first time fulfilled the quality criteria of temporal accuracy and precision, which are important prerequisites of visual experiments. Stimulus presentation is *temporally accurate* if the stimulus appears at the point in time and for the duration specified by the experimental design. Stimulus presentation is *temporally precise* if, across presentations, the stimulus appears at the same point in time after its presentation has been issued and for the same duration. Using the new apparatuses, it was possible in the 19th century to present stimuli too briefly for eye movements to be made, so that confounding influences of eye movements on visual performance could be circumvented (e.g., Volkmann, 1859). In addition, the brief, temporally accurate, and precise presentation opened up a wide range of research questions that could be addressed. For example,

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Cattell (1886) devised an apparatus that could present visual stimuli briefly and register observers' reactions to them in a time-locked manner. On the basis of observers' reaction times, he provided one of the first accounts of the time necessary to process visual information for conscious perception.

Stimulus presentation in vision research: the state of the art

Nowadays, most studies of vision and visual cognition are computer-based so that the classic apparatuses for visual presentation (e.g., tachistoscopes; Benschop, 1998) have widely been replaced by computer screens (e.g., Bauer, 2015; Ghodrati, Morris, & Price, 2015). These screens provide a number of advantages. Computer control allows to display a great variety of visual stimuli in an automated way that is relatively easy to implement. Different types of computer screens are currently available. The cathode-ray tube (CRT) has long provided the visual presentation with the highest temporal accuracy and precision and is still most commonly used for research purposes (e.g., Bauer, 2015; Ghodrati et al., 2015). Flat computer screens, such as liquid-crystal displays (LCD) and light-emitting diode displays (LED), have long been rare in vision research, because they lacked the necessary temporal accuracy and precision (Elze & Tanner, 2012). This problem has been solved by more recent flat screens designed specifically for vision research (e.g., the ViewPixx 120-Hz monitor, VPixx Technologies, Saint-Bruno, QC, Canada; Ghodrati et al., 2015). Likewise, there are now projectors for vision research providing high temporal accuracy and precision (as well as high refresh rates; e.g., 500 Hz in color in the ProPixx projector, VPixx Technologies, Saint-Bruno, QC, Canada). However, both device types are relatively expensive as compared to standard CRT and flat screen monitors.

In sum, current CRT screens, research flat screens, and research projectors warrant the relatively high temporal accuracy and precision necessary for experimental investigations of vision and visual cognition. However, one aspect of stimulus presentation remains challenging: All of these display devices allow to present visual stimuli with high temporal accuracy and precision but their temporal resolution is limited. The *temporal resolution* is the minimum temporal spacing between two successive stimulus onsets and thus the minimum presentation duration of one stimulus. For example, one screen refresh of a CRT with a refresh rate of 100 Hz takes 10 ms, so that each stimulus must be shown for at least 10 ms before the next stimulus, and it can only be shown for multiples of 10 ms. This imposes a fundamental constraint on how fine-grained stimuli can be presented temporally, which affects a wide range of research fields.

In experimental psychology, a number of key issues can only be investigated by means of a parametric variation of visual stimulus duration (e.g., Averbach & Coriell, 1961; Bundesen, 1990; Enns & Di Lollo, 2000; Raymond, Shapiro, & Arnell, 1992; Sperling, 1960). Studies of visual attention and object recognition, for instance, critically rely on measurements of visual processing speed, assessed as the rate at which object recognition performance increases over stimulus presentation durations that are increased in small steps (Bundesen & Harms, 1999; Shibuya & Bundesen, 1988). This gradual increase in presentation duration enables to study a number of stimulus factors (e.g., Petersen & Andersen, 2012) and cognitive mechanisms (such as visual attention, Bundesen, 1990; temporal expectation, Vangkilde, Coull, & Bundesen, 2012; Vangkilde, Petersen, & Bundesen, 2013; and event monitoring, Poth, Petersen, Bundesen, & Schneider, 2014) that are assumed to impact on visual processing speed. Although such studies have provided insights into temporal aspects of vision and visual cognition in the past, further progress may be hindered by the limited temporal resolution of the visual stimulus presentation. This may be the case because a low temporal resolution can hide data patterns, such as variations in the minimum presentation duration necessary to recognize an object and variations of processing capacity across trials (see, e.g., Dyrholm, Kyllingsbæk, Espeseth, & Bundesen, 2011; Petersen & Andersen, 2012).

A novel method for visual presentation with ultrahigh temporal resolution based on G-Sync

Here we introduce a novel method for presenting visual stimuli with ultrahigh temporal resolution on a commercially available and affordable LED-backlight LCD gaming monitor. The method is based on the G-Sync technology, which provides a crucial advantage over previous display technologies: Stimuli can be displayed almost immediately after they have been produced by the graphics card.

Figure 1 illustrates the general cycle of a stimulus presentation: The application sends drawing (or rendering) commands to the graphics card (GPU), which processes these commands in order to generate (or render) the image to be displayed next. This image is stored in a special buffer on the GPU, the so-called (front) *frame buffer*. The computer monitor reads out and displays the content of the GPU frame buffer, which typically happens row by row from the top-left to the bottom-right screen corner. On standard monitors, this proceeds at a fixed refresh rate (e.g., 100 Hz).

To avoid flickering artifacts during the incremental image generation process, most graphics applications employ double buffering: The new image is rendered into an invisible back buffer, and once the rendering is finished, the front and back buffers are swapped, such that the monitor reads out the new image from the front frame buffer on the next screen refresh.

Without synchronization between the GPU and the monitor, the buffer swap and the buffer read-out can be performed

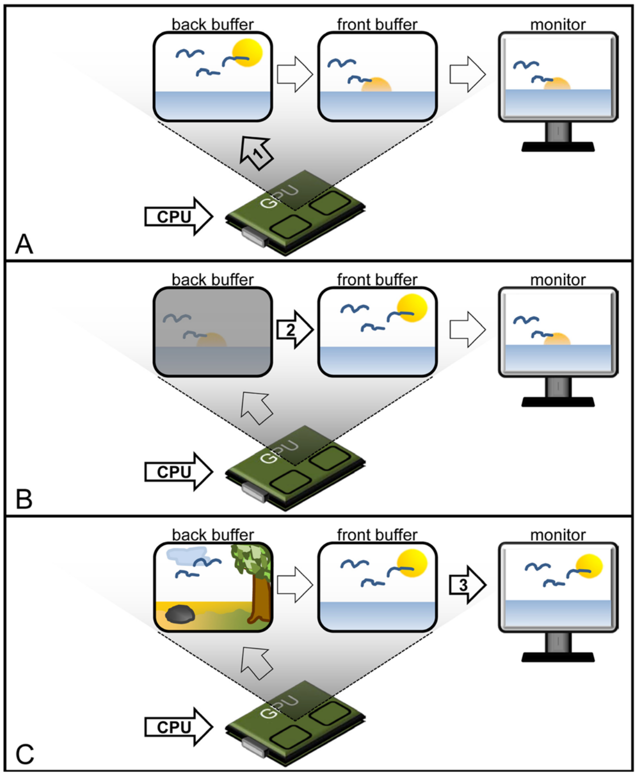

Fig. 1 General cycle of a stimulus presentation on a computer monitor with double buffering. The graphics card (graphics processing unit = GPU) processes a new drawing command from the application. The images are then rendered by the GPU and stored in a double buffering process. (A) In a first step, the new image is rendered into an invisible back buffer. The old image is still stored in the front buffer and displayed on the monitor. (B) In a second step, the back and front buffers are swapped. (C) In a third step, the monitor reads out and displays the content of the front buffer while a new image can already by rendered to the back buffer

simultaneously, and a serious problem can emerge: Although the monitor is reading out the (old) front buffer content, and has already read the upper part of the image, the two buffers are swapped, such that the lower part of the image is read from the new, updated front buffer. This disturbing effect, in which the old and new frame are mixed on the screen, is called *tearing*. It is effectively prevented by synchronizing GPU and monitor through V-Sync (vertical synchronization), whereby the buffer swap is delayed until the monitor has finished reading out the current frame buffer. In other words, the swap is performed during the vertical retrace of the monitor. V-Sync therefore ensures a tearing-free stimulus presentation by synchronizing the GPU to the monitor, such that the monitor triggers the GPU's buffer swap.

In both cases, with or without V-Sync, the displayed screen content cannot be changed at a temporal resolution higher than the screen refresh rate. This places a fundamental constraint on the temporal resolution at which stimuli can be presented. They can only be displayed for multiples of the single-frame time—which is, for instance, 10 ms for 100-Hz CRT monitors, or 16.7 ms for 60-Hz LCD screens.

In contrast to V-Sync, G-Sync allows for displaying stimuli on screen almost immediately after the graphics card has finished rendering them. The G-Sync technology was developed by Nvidia (Santa Clara, CA, USA) to reduce stutter in high-performance computer games. Instead of synchronizing the GPU's buffer swap to the monitor's fixed refresh rate, it works the other way around: The GPU triggers the screen refresh through its buffer swap. As soon as the GPU has rendered the new image into the back buffer, it performs the buffer swap, and the monitor reads out the frame buffer and displays its content. The screen refresh rate is then no longer fixed at 60 or 100 Hz, but can vary in the range of 30 to 144 Hz, which is guaranteed by the G-Sync specification. However, even the highest frequency of 144 Hz is not sufficient for a very high temporal resolution, since it implies a single-frame time of 7 ms, and thus only allows for presentation durations of multiples of 7 ms.

Exploiting the G-Sync technology in order to delay—instead of to accelerate—the GPU rendering is the key to achieve an ultrahigh temporal resolution with sub-millisecond steps of presentation durations. If a visual stimulus A is to be presented for k milliseconds, followed by a stimulus B, we proceed as follows: We render stimulus A into the back buffer, perform the buffer swap (which triggers screen refresh), and start a timer. While A is shown on screen, we render stimulus B into the back buffer but then delay the buffer swap until the k milliseconds of A's presentation duration are over. The buffer swap will then immediately trigger the screen refresh and replace stimulus A by B, resulting in a presentation duration of k milliseconds. The only condition on the duration k is that it has to be at least 7 ms (due to the 144-Hz maximum screen refresh rate, which in many cases is below the minimally required presentation duration for conscious perception; e.g., Bundesen & Harms, 1999). As long as it exceeds 7 ms, however, k can be increased in sub-millisecond steps. Thus, to summarize, our new presentation method enables stimulus durations to be controlled in a very fine-grained manner, provided that the presentation times exceed a specific minimum duration (7 ms for our 144-Hz monitor).

The following report is divided into four sections. First, we describe implementations in the three different programming languages C++, Python 2.7 (Python Software Foundation, Beaverton, OR, USA) with the PsychoPy2 extension (v1.85.2; Peirce, 2007, 2009; Listing 1), and Matlab (2015b; The Mathworks, Natick, MA, USA) with the Psychtoolbox3 extension (3.0.14; Kleiner et al., 2007). Second, for all three implementations, we report a test confirming the ultrahigh temporal resolution of visual presentation with external measurements using a photodiode. Third, we apply the presentation method in an actual psychophysical experiment, which revealed that the ultrahigh temporal resolution impacts on human visual performance. Fourth, we provide practical recommendations for using the presentation method in psychological and neuroscientific experiments.

Implementations of the new presentation method in C++, Python, or Matlab

In this section, we provide the required technical details and three different software implementations of the new G-Sync-based presentation method. The full source code for all software implementations is available in the supplemental materials. We demonstrate the method by presenting a *stimulus* in between a *prestimulus* baseline and a *poststimulus* baseline period. As we explained above, the main idea is to delay the buffer swap that brings on the poststimulus after the stimulus until the specified stimulus duration is over. Since G-Sync causes the buffer swap to trigger a screen refresh, the stimulus will be on screen for the specified duration.

In our examples, the stimulus is a white screen, and both the prestimulus and poststimulus are black screens. For other stimulus types, the method can be used analogously by assigning arbitrary visual textures to the stimulus objects (e.g., by assigning an arbitrary Psychopy stimulus to the "preStim" object in Listing 1). After the stimulus is displayed by a buffer swap, a function is called that waits for a prespecified stimulus duration using a high-precision timer (see the section called Stimulus in Listing 1). Only afterward does the poststimulus extinguish the stimulus with the next buffer swap (see the section called Poststimulus in Listing 1).

As we explained above, the G-Sync technology works by automatically adjusting the screen refresh rate to the temporal frequency at which the last few buffer swaps have been triggered. Importantly, this means that to present the stimulus for exactly k ms, the monitor must already be running at the required refresh rate of $1000/k$ Hz when switching from prestimulus to stimulus. We achieve this by adjusting the refresh rate during the presentation of the prestimulus; that is, we redraw the prestimulus every k ms during its presentation time (here, ~1000 ms; see the section called Prestimulus Adaptation of Monitor Refresh Rate in Listing 1). In all our experiments, ~1000 ms (i.e., 1000 ms/Stimulus Duration × Stimulus Duration) of prestimulus duration were sufficient for adjusting the monitor's refresh rate (as confirmed by the low standard deviation of the measured stimulus durations; see our results below).

```
# Pre-stimulus adaptation of monitor refresh rate.
for j in range(int(round(1 / duration))): # For about 1 s,...
    preStim.draw()    # ...draw the pre-stimulus (into the back buffer),...
    win.flip(False)   # ...display it by performing a buffer swap,...
    myWait(duration)  # ...and wait for the specified duration.

# Stimulus.
stim.draw()          # Draw the stimulus,...
win.flip()           # ...display it (clearing the back buffer afterwards),...
myWait(duration)     # ...and wait for the specified duration.

# Post-stimulus, which terminates the presentation of the stimulus.
postStim.draw()
win.flip(False)
myWait(1)
```

Listing 1 Snippet of computer code for implementing the presentation method in Python, using PsychoPy2. "Duration" is the desired stimulus duration in seconds. The full code is provided as supplemental material.

Triggering the monitor to update its screen content with the correct timing is only one crucial factor for precisely controlling presentation durations. Apart from that, the per-pixel transitioning from old to new color values has to be fast enough to ensure precise timing and to prevent ghosting artifacts (Elze & Tanner, 2012; Ghodrati et al., 2015). Our G-Sync gaming monitor (ASUS ROG Swift PG278Q) has a sufficiently short specified pixel switch time of 1 ms (https://www.asus.com/de/Monitors/ROG_SWIFT_PG278Q/specifications/). However, to achieve this fast pixel switch rate in actual experiments, the monitor has to be used in overdrive mode (using the recommended "medium" setting), in which higher voltages are used to speed up the pixel-transitioning process.

Confirmation of the ultrahigh temporal resolution of visual presentation

We confirmed that our method indeed provides an ultrahigh temporal resolution of stimulus presentation by measuring different stimulus sequences with a photodiode measurement circuit connected to an oscilloscope. This procedure is regarded as the gold standard for checking the timing of visual stimulus presentation (e.g., Ghodrati et al., 2015). In addition, we followed an increasingly popular approach and tested the method in a psychophysical experiment (Lagroix, Yanko, & Spalek, 2012; Semmelmann & Weigelt, 2016) measuring object recognition performance. This was aimed at investigating whether the ultrahigh temporal resolution of visual stimulus presentation has measurable effects on observers' visual performance. To this end, we adapted a well-investigated paradigm that assesses object recognition as a function of objects' presentation durations in order to estimate the temporal perceptual threshold and the speed of visual processing (e.g., Bundesen & Harms, 1999; Petersen & Andersen, 2012; Shibuya & Bundesen, 1988). Based on an existing mathematical model of psychophysical performance in this paradigm (Bundesen, 1990; Dyrholm et al., 2011; see also Petersen, Kyllingsbæk, & Bundesen, 2012), we could make specific predictions regarding observers' performance and test them against data from our new presentation method. In this way, we could show that the ultrahigh temporal resolution of the method impacts on object recognition performance as intended. This demonstrates the usefulness of the method for vision science, experimental psychology, and cognitive neuroscience.

Apparatus

The computer screen was the ASUS ROG Swift PG278Q (ASUS, Taipei, Taiwan) gaming monitor (27-in.), running at a resolution of 2560 × 1440 pixels with a refresh rate of 144 Hz, and employing the G-Sync technology (ASUS, Taipei, Taiwan). The screen was warmed up before use (cf. Poth & Horstmann, 2017) and controlled by an Nvidia GeForce GTX 1080 graphics card (Nvidia, Santa Clara, California, USA) and a Dell computer (Dell, Round Rock, Texas, USA; Intel Xeon E5-1620, 8GB Ram) operated by Windows 7 64-bit (Microsoft, Seattle, Washington, USA).

External measurements of stimulus duration using photodiode and oscilloscope

Measurement Display timing was measured by means of a photodiode measurement circuit with a 9-V battery supply using a high-speed silicon photodiode (BPW34, Vishay Semiconductors, Malvern, PA, USA) and a 390-kΩ resistor connected to an oscilloscope (TDS 2022B, Tektronix, Beaverton, OR, USA) with a sampling frequency of 100 kHz (see Fig. 2 for a circuit diagram). The photodiode output was monotonically dependent on the luminance of the stimulus.

Luminance and chromaticity were measured with a spectrophotometer (i1 Pro, X-Rite, Munich, Germany) and are reported in CIE Lxy coordinates. The photodiode was placed 2 cm below screen center. We tested the above-described implementations of the presentation method displaying a white screen as stimulus (L = 373.9 cd×m^{-2}, x = 0.31, y = 0.32) in between pre- and post-stimulus baselines of a black screen (L = 0.2 cd×m^{-2}, x = 0.25, y = 0.26). The duration of the white screen was first varied in a fine-grained fashion, that is, in steps of 0.5 ms by using the durations 7, 7.5, 8, 8.5, and 9 ms. To assess the timing for longer presentation durations, measurements for the durations of 23 and 50 ms were included in addition. Ten measurements were taken per each of the presentation durations.

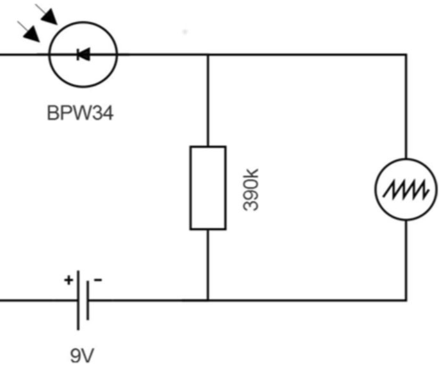

Fig. 2 The circuit for measuring display timing, utilizing a reverse-biased photodiode (BPW34) working as current source in series with a resistor (390k). The voltage change over the resistor, caused by the light change measured by the photodiode, is measured by an oscilloscope

Moreover, to assess the effect of gray-to-gray changes on a given stimulus duration, we measured 50-ms stimuli, using the PsychoPy2 implementation to test the following combinations of baseline and stimulus gray levels (given as percentages of the luminance of the white screen, which is the monitor's maximum luminance): 0%–100% (i.e., black–white), 10%–90%, 20%–80%, 30%–70%, and 40%–60%. Likewise, to assess the effect of gray-to-gray changes on the temporal resolution of visual presentation, we measured the full set of presentation durations (as for white stimuli) for the 30%–70% baseline and stimulus, also using the PsychoPy2 implementation.

Results Figure 3 depicts the raw data of a single measurement for each of the seven durations of the white-screen stimuli (using the PsychoPy2 implementation). The voltage output of the photodiode (in volts) is plotted as a function of time (in milliseconds). The voltage output rises in response to the onset of the white screen, stays elevated for its presentation duration, and drops back to baseline afterward. Already visible in these raw data, the stimulus durations between 7 and 9 ms terminated one after the other, indicating an ultrahigh temporal resolution. To quantify the stimulus timing, we defined the measured onset and offset of the white screen as the time at which the photodiode output rose above or dropped below a threshold of (minimum voltage + maximum voltage)/2 (in the respective measurement trial; see the blue dashed line marking stimulus onset in Fig. 3). Noise-induced threshold crossings within an interval of 1 ms after stimulus onset were not counted as stimulus offset.

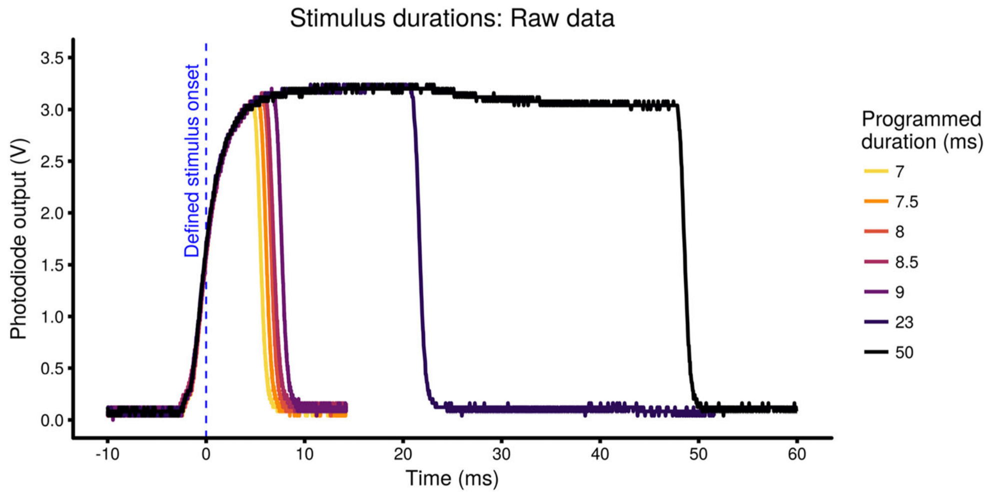

Fig. 3 Raw data of external measurements of the stimuli, shown for different durations (using the PsychoPy2 implementation). The blue dashed line indicates the stimulus onset, defined as the time when the voltage output of the photodiode rose above a threshold (see the text)

Figure 4 depicts the raw data of a single measurement for the different gray stimuli. These data show that both the stimulus rise and its decay to baseline are steepest for white stimuli against a black pre- and poststimulus baseline, and shallower for gray stimuli against darker gray baselines (a well-known characteristic of LCD displays; e.g., Ghodrati et al., 2015).

Figure 5 shows the mean stimulus durations and corresponding 95% confidence intervals over ten trials for white stimuli shown for 7, 7.5, 8, 8.5, 9, 23, or 50 ms against the black baseline (0%–100%) for each of the three software implementations and for the additional 70%-gray stimulus against the 30%-gray baseline (30%–70%). As is evident from Fig. 5, for all measured implementations and stimuli, the confidence intervals of one stimulus duration did not overlap with the confidence interval of the next. These data indicate that the measured stimulus durations were temporally as fine-grained as intended. Thus, the stimuli were indeed shown with ultrahigh temporal resolution.

A crucial limiting factor for the temporal resolution of visual presentation is the absolute variability of stimulus durations. Table 1 provides the standard deviations and means for all measured stimulus durations. In comparison, the C++ implementation had the lowest standard deviations (all *SD*s were below 0.04 ms). However, also the two high-level implementations based on Python's PsychoPy2 (Peirce, 2007, 2009) and Matlab's Psychtoolbox3 (Kleiner et al., 2007) achieved standard deviations enabling an ultrahigh temporal resolution (all *SDs* were below 0.13 ms).

As is evident from Fig. 5 and Table 1, the stimulus durations of the white stimuli fell short of the programmed stimulus durations. This presentation error is due to the slightly shallow rise and fall time of voltage output in response to stimulus onset and offset (see Fig. 5). Overall, the presentation error was below 1.61 ms (M = 1.04 ms, SD = 0.72) for all implementations, durations, and stimuli. Together with the low variability (see the *SD*s in Table 1), this means that the presentation error was

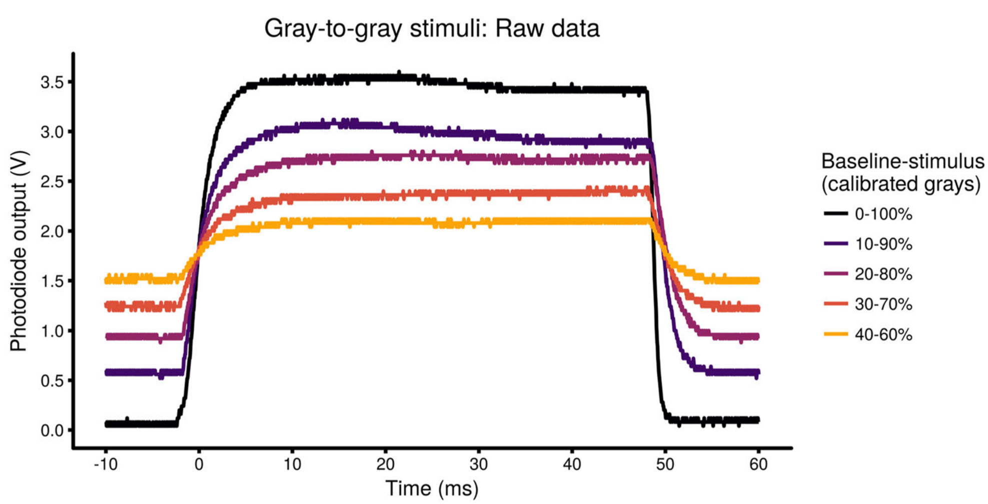

Fig. 4 Raw data of external measurements of different gray or white stimuli, shown for 50 ms against baselines of, respectively, darker grays or black (using the PsychoPy2 implementation)

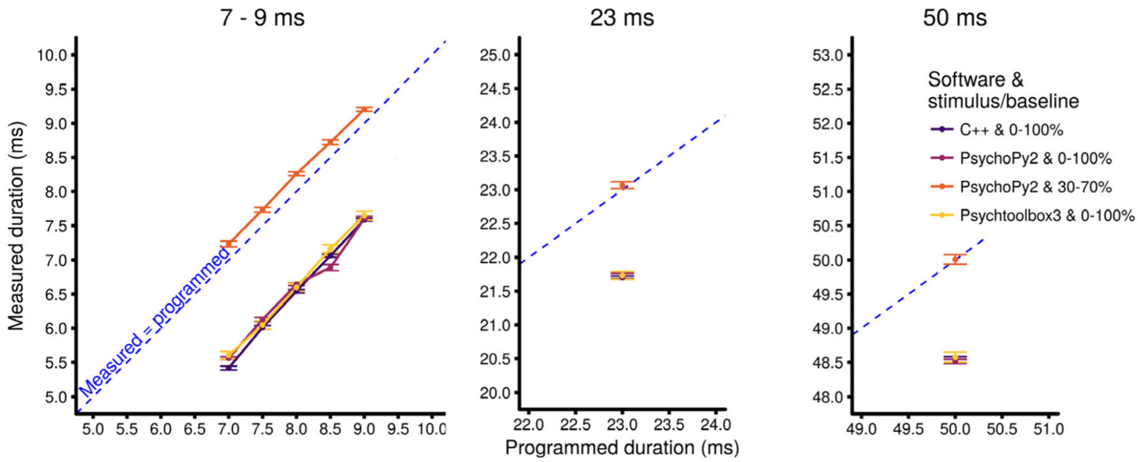

Fig. 5 Mean measured presentation durations for seven programmed presentation durations and all three software implementations. Data are provided for white stimuli against black baselines (i.e., 0%–100%) and an additional 30%–70% combination of baseline and stimulus. Error bars indicate 95% confidence intervals. Blue dashed lines indicate identity of the programmed and measured stimulus durations

relatively constant. Thus, to compensate for the error, it can be added to the programmed stimulus duration once it has been measured externally. For the 70%-gray stimulus, the presentation error was much smaller than for the white stimuli (the orange data points in Fig. 5). Compared with the white stimuli against the black baseline, the gray stimuli exhibit even a shallower rise and a prolonged decay of the stimulus to baseline (see Fig. 4). Thus, where the shallowness of the stimulus's rise and fall cuts the presentation duration for the white stimulus, it prolongs the duration for the gray stimuli (see Fig. 4). Overall, this indicates that the correction compensating for presentation error should be performed for all stimuli individually (see the Discussion section).

Psychophysical experiment for measuring letter report performance

The aim of the psychophysical experiment was to test whether a high temporal resolution of visual stimuli has measurable effects on human object recognition performance assessed as letter report. To this end, observers viewed and reported letters that were shown briefly, for several fine-grained durations, and terminated by backward pattern masks. Performance was then assessed as letter report accuracy and was analyzed as a function of fine-grained presentation durations. On the basis of well-investigated mathematical models of object recognition, we could make specific predictions of how performance should improve with increasing presentation duration, leading to estimates of observers' temporal perceptual thresholds and visual processing speeds (Bundesen, 1990; Dyrholm et al., 2011).

Method

Apparatus The computer monitor of the psychophysical experiment was the same as described above. The psychophysical experiment took place in a semi-lit room. For the experiment, a decorative ring of red light at the foot of the monitor was covered with duct tape. Observers viewed the monitor

Table 1 Means and standard deviations of measured stimulus durations for all software implementations and stimuli

Programmed duration	C++ & 0%–100%		PsychoPy2 & 0%–100%		PsychoPy2 & 30%–70%		Psychtoolbox3 & 0%–100%	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
7	5.42	0.04	5.56	0.03	7.24	0.07	5.60	0.09
7.5	6.01	0.04	6.13	0.05	7.73	0.06	6.05	0.10
8	6.54	0.04	6.64	0.03	8.26	0.05	6.60	0.09
8.5	7.06	0.04	6.89	0.07	8.72	0.06	7.17	0.09
9	7.59	0.03	7.60	0.06	9.20	0.05	7.65	0.10
23	21.70	0.03	21.72	0.07	23.07	0.08	21.73	0.09
50	48.56	0.03	48.51	0.05	50.01	0.11	48.58	0.12

Programmed durations, means (*M*), and standard deviations (*SD*) in milliseconds from a distance of 71 cm with their heads stabilized by a headrest. Responses were collected using a standard keyboard with QWERTZ layout.

Observers Four observers were paid to perform the experiment. They were 23, 24, 24, and 25 years old. Observers 1, 2, and 3 were female, and Observer 4 was male. All observers stated being right-handed. All observers reported normal or corrected-to-normal visual acuity and normal color vision (Observers 2 and 4 wore glasses). Written informed consent was obtained from the observers before the experiments, which was conducted according to the ethical standards of the German Psychological Association (DGPs). The experiment was approved by Bielefeld University's ethics committee.

Stimuli The stimuli were 20 red (L = 39.9 cd×m^{-2}, x = 0.65, y = 0.34) uppercase letters [ABDEFGHJKLMNOPRSTUVX] (Arial font, 68 pt, approximately 1.83° × 1.83° [degrees of visual angle], displayed on the monitor with unlinearized gamma). These letters were chosen to reduce confusability (cf. Poth & Schneider, 2016a, b). The letters were red because this is the color most commonly used in such experiments (e.g., Foerster, Poth, Behler, Botsch, & Schneider, 2016; Vangkilde, Bundesen, & Coull, 2011; Vangkilde et al., 2012, 2013). Eight different masks were used (from Vangkilde et al., 2011). They were composed of red (L = 44.2 cd×m^{-2}, x = 0.60, y = 0.34) and blue (L = 21.2 cd×m^{-2}, x = 0.16, y = 0.07) letter fragments and covered an area of 2° × 2°. A gray "plus" character was used as central fixation cross (L = 92.5 cd×m^{-2}, x = 0.30, y = 0.31; 1.3° × 1.3°).

Procedure and design Figure 6 illustrates the paradigm of the psychophysical experiment. Each trial began with the presentation of a central fixation cross for ~800 ms, which stayed on screen throughout the trial. Afterward, a letter was shown for one of 17 durations (0, 7, 9, 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, 31, 50, 70, or 90 ms). The letter was randomly chosen from the set of letters employed (according to a uniform distribution; a unique random sequence was created for every observer and every session). On trials in which no letter was shown (presentation duration = 0 ms), a randomly chosen letter was recorded as having been shown. The letter appeared at one of two locations at 3.77° to the left or right of screen center (at which location the letter appeared was randomized across trials, both locations occurring equally often). Following the letter, two pattern masks (randomly chosen without replacement from the set of masks used) were presented for 500 ms at the two possible letter locations. At the end of a trial, observers reported the letter by typing it into the keyboard. The typed-in letters were shown on screen so that observers could confirm their report by pressing the spacebar. Reports were forced-choice: Observers were required to report a letter, guessing in the case that they were uncertain of the letter that had been presented. Confirmation of the report started the next trial.

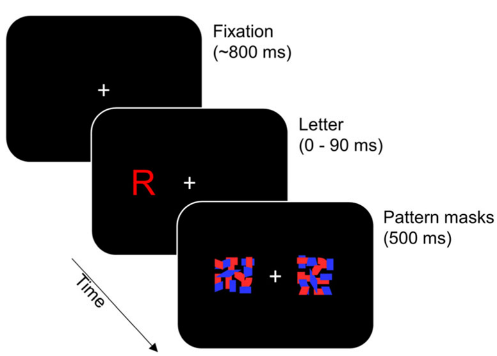

Fig. 6 Experimental paradigm. On a trial, observers viewed a single letter for one of 17 presentation durations between 0 and 90 ms. The letter appeared at one of two locations, to the left or right of screen center. Following the letter, two pattern masks were shown for 500 ms at each possible letter location. Letter presentation was preceded by a fixation period during which observers were to fixate a central fixation cross. At the end of a trial, observers reported the letter using the keyboard, guessing if they were uncertain about which letter had been shown

Observers performed 2040 trials across three sessions on three separate days. That is, each session comprised 680 trials, or 40 trials per presentation duration of the letter (20 per each of the two presentation locations).

Implementation using G-Sync and C++

The G-Sync implementation used for the psychophysical experiment is equivalent to the C++ implementation described in the supplemental materials. The prestimulus is now the fixation cross (~800 ms), the stimulus is the random letter, and the poststimulus are now the two masks (500 ms).

External measurement of stimulus duration by a high-speed camera

As is shown by Fig. 4, the presentation durations of stimuli may depend on their luminance. Because the small red letters were hard to capture with the photodiode, we checked the stimulus timing of the psychophysical experiment by recording stimulus sequences of single trials with a high-speed camera sampling at 1200 Hz (J4, Nikon, Tokio, Japan). We recorded the stimulus sequence of ten trials for each of the letter presentation durations of 7 and 9 ms. By counting the camera frames (in the resulting video files) for which the letters were shown on a given trial, we obtained an approximate confirmation that the letter stimuli were shown as temporally fine-grained as intended. That is, the confidence intervals for the two durations did not overlap: 7-ms stimulus: M = 6.33 ms, SD = 0.43 ms, CI = [6.07 ms; 6.60 ms], 9-ms stimulus: M = 7.58 ms, SD = 0.26 ms, CI = [7.42 ms; 7.75 ms].

Results of the psychophysical experiment

Figure 7 depicts observers' letter report performance as a function of the presentation duration of the letters. Following the generalization of Bundesen's (1990) model by Dyrholm et al. (2011; see also Petersen et al., 2012), we assumed that letter recognition performance and presentation duration can be described by an ex-Gaussian psychometric function (for an overview and a comparison to other psychometric functions, see Petersen & Andersen, 2012). The general psychometric function

$$\psi(t;\theta,\gamma) = \gamma + (1-\gamma)\cdot F(t;\theta)$$

describes the probability of correct letter reports as a function of the presentation duration t of the letter, the parameter set θ, and the probability of guessing the correct letter γ, which was fixed at 1/20 letters for the present experiment with 20 letters (e.g., Petersen & Andersen, 2012). The ex-Gaussian psychometric function is obtained by using the cumulative ex-Gaussian distribution function (the following definition of the ex-Gaussian distribution is taken from Petersen & Andersen, 2012; see Petersen et al., 2012, Eq. 7 for an alternative)—that is,

$$F(t,\theta) = \Phi\left(\frac{t-\mu}{\sigma}\right) - \Phi\left(\frac{t-\mu-\frac{\sigma^2}{\tau}}{\sigma}\right)\cdot\exp\left(-\frac{t}{\tau}+\frac{\mu}{\tau}+\frac{\sigma^2}{2\tau^2}\right),$$

where Φ denotes the cumulative Gaussian distribution and has the parameter set $\theta = \{\mu, \sigma, \tau\}$, where μ (≥ 0) and σ (>0) are the mean and standard deviation of the Gaussian distribution, and τ (>0) is the mean of the exponential distribution. The parameters are interpreted as follows: μ and σ are the mean and standard deviation of the perceptual threshold (both in milliseconds), which is the maximum presentation duration that is ineffective so that it results in chance performance

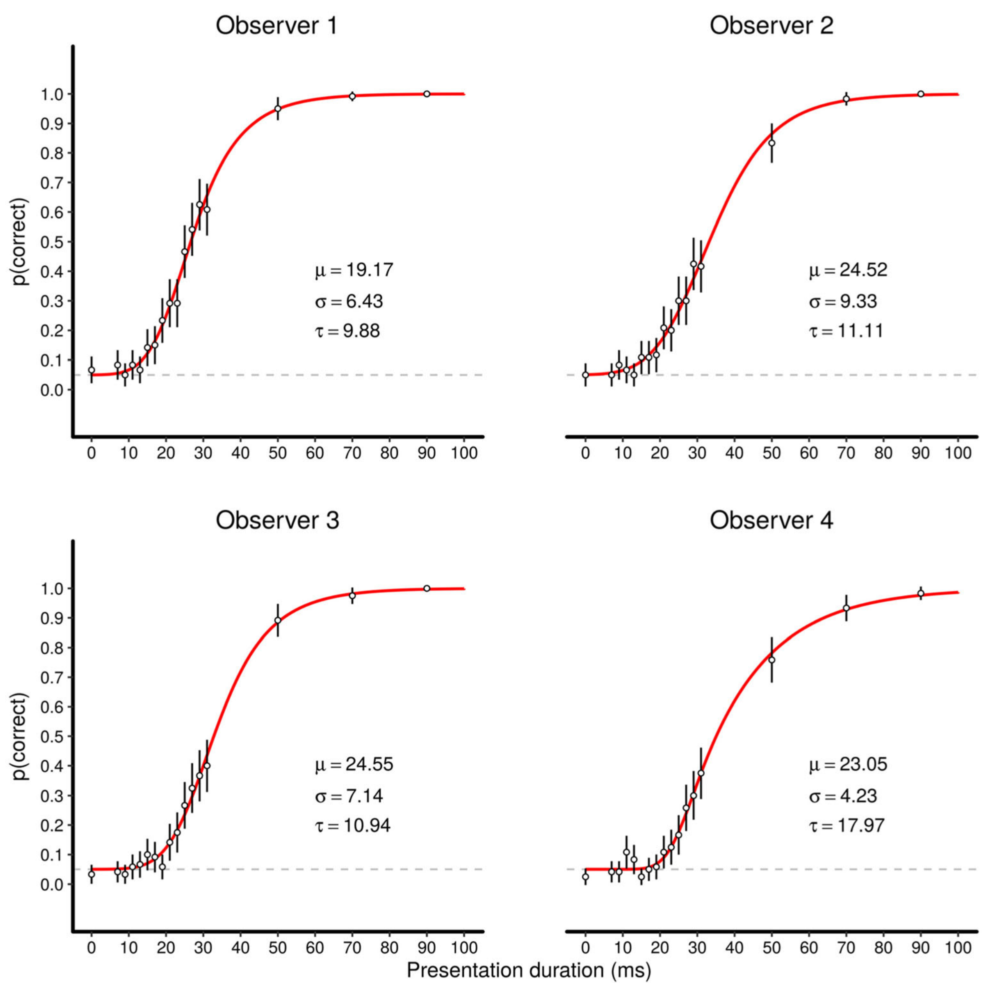

Fig. 7 Letter recognition performance as a function of the duration of the backward-masked letters for all four observers. Circles depict the observers' probabilities of correctly reporting the letters (i.e., the proportions of trials with correct reports). The gray dashed lines indicate chance level. Error bars indicate 95% confidence intervals based on the binomial distribution. The red smooth curves show maximum-likelihood fits of the ex-Gaussian psychometric function to the data. The estimated parameters of the ex-Gaussian psychometric function (μ, σ, and τ, all in milliseconds) are stated within the plot for each observer

(Dyrholm et al., 2011). $1/\tau$ represents an important variable of interest, namely the speed of visual processing (in letters/ms), and is commonly used to characterize visual-processing performance (e.g., Bundesen, 1990; Petersen et al., 2012; applications of the measure of visual processing speed for various patient groups are reviewed by Habekost, 2015).

Maximum-likelihood fits of the ex-Gaussian psychometric function to the data were obtained separately for each observer (using the optim function in R [3.3.1]; R Development Core Team, 2016). The resulting fits were excellent, so that the correlation (Pearson's r) between the predicted and observed probabilities of correct reports always exceeded .996. As can be seen in Fig. 7, letter recognition performance increased steadily with the increasing presentation duration of the letter. The performance increase closely followed the 2-ms increments of presentation duration. In this way, these data provide human behavioral evidence for the fine temporal grading of visual presentation capabilities of the G-Sync technology in combination with a state-of-the-art gaming monitor. This demonstrates the usefulness of the presentation technology by showing that small increments in presentation duration have an effect on human object recognition performance.

Discussion

We introduced a method for presenting visual stimuli with ultrahigh temporal resolution based on Nvidia's G-Sync technology (Santa Clara, CA, USA) and a gaming monitor. The G-Sync technology provides a decisive advantage over previous methods for visual stimulus presentation: Stimuli can be displayed almost immediately after they have been rendered by the computer's graphics card rather than having to wait until the next screen refresh. As a consequence, stimuli can be presented for durations graded with ultrahigh resolution, provided a minimum duration is exceeded. This minimum duration is specific to the monitor: Although it was 7 ms in the present setup (one frame at 144 Hz), it will be even shorter in the next generation of gaming monitors (e.g., 4 ms for the ASUS PG258Q, which has a refresh rate of 240 Hz; ASUS, Teipei, Taiwan).

We implemented the new presentation method using custom C++ software and two widely used and research-focused programming environments, the PsychoPy2 extension for Python 2.7 (Peirce, 2007, 2009) and the Psychtoolbox 3 extension (Kleiner et al., 2007) for Matlab (The Mathworks, Natich, MA, USA). For all three implementations, we confirmed that the G-Sync-based presentation method indeed provides ultrahigh temporal resolutions by externally measuring display timing with a photodiode measurement circuit and an oscilloscope. The stimuli for these measurements were a white screen shown for finely varied durations between pre- and poststimulus black-screen baselines. In addition to white screens, we also measured display timing for a 70%-gray stimulus against a 30%-gray baseline employing the PsychoPy 2 software implementation. All these external measurements confirmed that the stimulus presentation durations were as finely graded as intended.

Limitations and practical recommendations

Altogether, our method allows to present visual stimuli for durations of ultrahigh temporal resolution. It is important to note, however, that the presentation method also has limitations. First, to finely grade the duration of a stimulus, the method automatically adapts the monitor refresh rate by showing the preceding displays for the same duration. This is no problem for the bulk of experiments in psychology and neuroscience. Here, the stimuli of interest appeared after a blank interval, which is sufficient for adapting the refresh rate to the desired stimulus duration (e.g., Bundesen & Harms, 1999; Poth & Schneider, 2016a, b). However, for stimuli in rapid succession, different finely graded stimulus durations are not possible, because they require different refresh rates. In our psychophysical experiment, we adapted the refresh rate during the interval of a fixation cross, which was shown for ~800 ms before the stimulus. Such a prestimulus duration is well in line with typical experiments (e.g., Bundesen & Harms, 1999), but it could also be reduced if necessary. To this end, experimenters should confirm that they present enough preceding displays using external measurements.

Second, we observed that externally measured stimulus presentation durations fell short of programmed presentation durations because of shallow stimulus rise and fall times, which is characteristic to LCD displays (e.g., Ghodrati et al., 2015). This presentation error has little variability and thus can be circumvented by externally measuring stimulus durations and then correcting for the error in the programmed stimulus durations. Our measurements of different gray stimuli against darker gray baselines showed that the luminance rise and fall times may differ depending on stimulus features as color or gray value, which is a well-known characteristic of LCD screens (Elze & Tanner, 2012; see also Ghodrati et al., 2015; for a review, see Bauer, 2015). On the one hand, this means that measurements and the correction of presentation error should be performed for the specific stimuli individually. On the other hand, this provides an additional way of correcting for presentation errors, namely by adjusting (and beforehand measuring) stimulus luminance. This was evident from our duration measurements of the 70%-gray stimulus, which revealed smaller presentation errors, because the errors were compensated for by the prolonged rise from and decay of the stimulus to baseline.

Third, in experiments requiring the online computation of rapidly changing stimulus sequences (e.g., for motion stimuli), it may be necessary to control not only the temporal resolution of presentation but also its latency after stimulus creation. Moreover, stimuli shown at different screen locations might differ in their relative timing and visual characteristics, which should also be taken into account.

For all of these reasons, we recommend that experimenters using our method verify their presentation timing for their specific stimuli and stimulus sequences by external measurement, for instance using the measurement circuit presented above or a high-speed camera.

The temporal resolution of visual presentation impacts on human visual performance

To investigate whether the stimulus presentation with ultrahigh temporal resolution has measurable effects on human visual performance, we conducted a psychophysical experiment. The experiment employed a well-investigated paradigm, which assesses object recognition as a function of objects' presentation duration that is terminated by backward pattern masks (e.g., Bundesen & Harms, 1999; Petersen & Andersen, 2012; Shibuya & Bundesen, 1988). The objects in the experiment consisted of red letters shown against a black background (e.g., Foerster et al., 2016; Vangkilde et al., 2011, 2012, 2013). For these stimuli, we confirmed the ultrahigh temporal resolution using a high-speed camera.

For all observers, letter report performance increased with increasing presentation duration. Importantly, these increases closely reflected the finely graded stimulus durations of our presentation method. A number of psychophysical models can be used to quantify this relationship (Bundesen, 1990; Dyrholm et al., 2011; Petersen & Andersen, 2012; Shibuya & Bundesen, 1988). These models offer specific predictions of how performance should improve with increasing presentation duration. We based our predictions on the model by Dyrholm and colleagues, which we adapted to the forced-choice procedure of the present paradigm following Petersen and Andersen (2012). The model provided excellent fits to the data of all observers, indicating that object recognition performance matched the predictions of Dyrholm et al.'s model for the finely graded object presentation durations. In this way, the experiment shows that the ultrahigh temporal resolution of our presentation method measurably impacts on human visual performance and illustrates the use of the method for experimental psychology and cognitive neuroscience.

Potential of the new presentation method for psychology, neuroscience, and related fields

How may the presented method for temporally fine-grained visual presentation advance research on vision and visual cognition? As was demonstrated by the psychophysical experiment on object recognition performance, our presentation method allows to study visual processing with a temporal resolution that has not been provided by previous display technologies, employing standard computer monitors and standard ways of transferring images from the graphics card to the monitor. Therefore, the method opens up a new window for studying visual processes with data patterns that are concealed by a too low temporal resolution of previous technologies. For example, processes associated with variations in the minimum presentation duration necessary to report an object (see, e.g., Dyrholm et al., 2011; Petersen & Andersen, 2012) could not be detected with such traditional display technologies.

Current display devices with relatively high temporal resolution (500 Hz in color) are projectors especially designed for vision research (e.g., the ProPixx projector, VPixx Technologies, Saint-Bruno, QC, Canada). These projectors offer great precision and accuracy and a number of possibilities for vision research, such as efficient color calibration. However, these projectors are much more expensive and demand more laboratory space than standard computer monitors. In contrast, our presentation method requires a gaming monitor that has about 3% of the cost of the projector and demands much less laboratory space. Our presentation method thus makes the gaming monitor a cost-effective and feasible display solution for a wider employment in vision research.

Furthermore, the presentation method may help to overcome one limitation of the CRT screen, which is still the most commonly used monitor for research (e.g., Bauer, 2015; Ghodrati et al., 2015). That is, CRT screens display images as distinct frames in which the luminance (and chromaticity) ramps up steeply in the beginning and decays fast toward its end. Thus, showing a stimulus on a CRT means that the stimulus is not continuously present but instead consists in a number of luminance ramps and decays. These luminance changes are typically too rapid to be perceived by human observers (Ghodrati et al., 2015; but see Davis, Hsieh, & Lee, 2015). However, they have been shown to affect the activity of neurons throughout the visual pathways (Krolak-Salmon et al., 2003; Williams, Mechler, Gordon, Shapley, & Hawken, 2004; Wollman & Palmer, 1995). The consequences of this activity are unknown and not considered in explanations of visual processing that assume stimuli on CRTs as continuously present. Therefore, our presentation method may be used to vary presentation durations on a timescale fitting within a single CRT frame and to compare visual performance to a CRT. This may help to elucidate the effects of a finely graded intermittent presentation that is inherent to stimuli on CRTs.

Our implementations of the new presentation method were based on Nvidia's (Santa Clara, CA, USA) G-Sync technology. It shall be noted, however, that there is an alternative called FreeSync (AMD, Sunnyvale, CA, USA). We here decided for G-Sync, because it is a joint implementation/specification for graphics cards and monitors with strict specification requirements, which guarantee that adaptive refresh rates and overdrive pixel switching can be used simultaneously. However, achieving an ultrahigh temporal resolution of visual stimulus presentation might be possible with FreeSync as well.

Conclusion

In sum, we introduced a method for presenting visual stimuli with ultrahigh temporal resolution on commercially available gaming monitors. The method capitalizes on the G-Sync technology that synchronizes the computer's graphics card with the monitor. That this presentation method indeed provides ultrahigh temporal resolution was confirmed with external measurements based on a photodiode and an oscilloscope. In addition, the method was tested in a psychophysical experiment on object recognition of backward-masked letters, which revealed that the high temporal resolution indeed impacts on human visual performance. In this vein, the psychophysical experiment demonstrated the use of the method for experimental psychology and cognitive neuroscience. As such, the new presentation method may be valuable for research on vision and visual cognition that focuses on visual processing over time, for example in the areas of visual attention (e.g., Bundesen, Vangkilde, & Petersen, 2015; Nobre & Kastner, 2014; Schneider, 2013), visual masking (e.g., Breitmeyer & Öğmen, 2006; Enns & Di Lollo, 2000), and perception across eye movements (e.g., Poth, Herwig, & Schneider, 2015).

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