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Luminance and timing control during visual presentation of natural scenes

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ABSTRACT

In the study of visual cognition, accurate control of stimulus presentation is of primary importance yet is complicated by hardware malfunctioning, software variability, and visual materials used. Here, we describe VISTO 2.0, a low-cost and open-source device which is capable to measure the timing and temporal luminance profile of visual stimuli. This device represents a major improvement over VISTO (De Cesarei, Marzocchi, & Loftus, 2021), as it is only sensitive to a light spectrum in the visible range, is easier to assemble, and has a modular design that can be extended to other sensory modalities.

Specifications table

Hardware name	*VISTO 2.0*
Subject area	Neuroscience
Hardware type	Measuring physical properties and in-lab sensors
Closest commercial analog	*The Black Box ToolKit*
Open source license	*Creative Commons Attribution-ShareAlike license*
Cost of hardware	*Approximately 50 €*
OSF source file repository link	https://doi.org/10.17605/OSF.IO/4B7C5

Hardware in context

Investigating the processing of visual stimuli is of primary importance in the study of several topics such as attention, emotion, memory, and perception. In experiments investigating these topics, visual stimuli that are as diverse as color patches, shapes, object silhouettes, or natural scenes are usually presented to participants, while some visual aspects (e.g., contrast or exposure time) are manipulated. When such stimuli are presented, it is important that experimenters control that the desired physical manipulations are respected, e.g., that a brief-duration stimulus is actually presented for the requested time. Previous literature concentrated on the use of specific monitor technologies in psychology experiments (e.g., [1–4]), and we recently proposed a device to control for the onset and synchronization of visual stimuli (VISTO; [5]).

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2468-0672/

VISTO included a phototransistor which was sensitive to a wide spectrum of light, and its capability to accurately detect the onset and offset of visual stimuli was validated using uniform white patches. However, the phototransistor VISTO used was sensitive to a wide light spectrum, which includes infrared light that is outside the visible range. Here, we present a major development of VISTO, which is designed to be more modular, easier to assemble, and capable to accurately measure the luminance of natural scenes in the visible spectrum. Importantly, it is not the primary aim of VISTO 2.0 to achieve a colorimetric measure, which would require different sensors, hardware and calibration. Instead, VISTO 2.0 is aimed at measuring the temporal luminance profile of visual stimuli, and to assess stimulus onset and offset times based on these temporal luminance profiles. This can be done prior to running an experiment, when hardware and software parameters must be set to ensure maximum reliability of the instrumentation.

Natural scenes

Natural scenes are pictures taken from the real world, that vary considerably from each other in terms of brightness, contrast, and composition. These visual stimuli contain several features such as edges, contours, shades, etc., that span the spatial frequency range and make stimulus appearance considerably variable. Moreover, these categorical differences can be systematic, as in the case of visual scene statistics that characterize specific contents (e.g., [6–8]). For instance, indoor and outdoor scenes differ systematically in terms of light source, and distribution of lighter and darker areas in the scene. As monitor performance, in terms of the time-luminance profile that describes the transition from dark to bright, is not instantaneous and diverge from a theoretical square wave [5], it may well be that differences among images also result in timing differences in onset time or exposure time. It is therefore important to develop an instrument that can report, for different visual stimuli, the temporal variations in luminance profile.

Hardware description

Here we present VISTO 2.0, which is a major development of VISTO [5] that can measure the timing and temporal luminance profile of the presentation of visual stimuli on LCD monitors. VISTO 2.0 includes several changes compared with the original VISTO:

- a sensor with spectral sensitivity in the visible range;
- an increased signal-to-noise ratio;
- better output linearity;
- easier assembly;
- a modular design.

One major change in signal acquisition was changing from the previous BPW42 phototransistor sensor, with maximum sensitivity at 830 nm connected in common-collector amplifier mode, to the present BPW21R photodiode sensor with 420–675 nm sensitivity. Importantly, this sensor has some similarities with the human eye sensitivity, but has also differences, e.g., in the sensitivity in the blue and red spectral ranges. Due to the lower sensitivity of photodiode sensor, the signal was amplified by a transimpedence circuit using an OpAmp, which permits wide linearity and low noise signal [9]. Finally, VISTO 2.0 was designed to be modular, i.e., to be able to perform the presented analyses using any sensor that can provide a continuous signal between 0 and 1.1 V (range modifiable via software).

Design files

Design files summary

Design file name	File type	Open source license	Location of the file
Design file 1	KiCAD project file	*Creative Commons Attribution-ShareAlike license*	*Available at https://doi.org/10.17605/OSF.IO/4B7C5*
Design file 2	KiCAD project file	*Creative Commons Attribution-ShareAlike license*	*Available at https://doi.org/10.17605/OSF.IO/4B7C5*

Design file 1. Project for the main VISTO 2.0 unit (shield), comprising connections to the LCD screen connector, scaling buttons, an opto-isolator circuit to the triggering signal (TRIGGER), and a light sensor connector (A0) (KiCad 5.1.12 https://www.kicad.org/).

Design file 2. Projects for the light sensor unit (KiCad 5.1.12 https://www.kicad.org/).

Bill of materials summary

Shield

Designator	**Component**	**Number**	**Cost per unit - currency**	**Total cost-currency**
A0,A1,A2, A3	Connector_JST:JST_XH_B2B-XH-A_1x02_P2.50mm_Vertical	4	< 1 €	< 1 €
D1	LED_THT:LED_D5.0 mm Trigger LED YELLOW DIFFUSED T-1 3/4 T/H	1	< 1 €	< 1 €
J1	Connector_PinSocket_2.54 mm:PinSocket_1x16_P2.54mm_Vertical for LCD	1	< 1 €	< 1 €
R1	Resistor_THT:R_Axial_DIN0207 value 220 ohm 5 % 1/4W	1	< 1 €	< 1 €
> R2, R4	Resistor_THT:R_Axial_DIN0207 value 10 k ohm 5 % 1/4W	2	< 1 €	< 1 €
> R3, R5	Resistor_THT:R_Axial_DIN0207 value 390 ohm 5 % 1/4W	2	< 1 €	< 1 €
RV1	Potentiometer_THT:Potentiometer_Bourns_3296W value 10 k ohm 0.5 W PC PIN TOP	1	< 1 €	< 1 €
White btn	Switch_Tactile_THT_6x6mm (suggested cap color White)	1	< 1 €	< 1 €
Black btn	Switch_Tactile_THT_6x6mm (suggested cap color Black)	1	< 1 €	< 1 €
Trigger1	Connector_JST:JST_XH_B2B-XH-A_1x02_P2.50mm_Vertical	1	< 1 €	< 1 €
U1	Optoisolator 4N35 IC Package_DIP:DIP-6_W7.62 mm	1	< 1 €	< 1 €
XA1	Arduino Mega 2560 shield (pcb by your preferred manufacturer)	1	< 1 €	< 1 €

Light sensor

Designator	Component	Number	Cost per unit-currency	Total cost-currency
C1	Capacitor_THT:C_Rect_L7.0mm_W2.0mm_P5.00 mm 220nF polyester	1	< 1 €	< 1 €
> C2-C4	Capacitor_THT:C_Rect_L7.0mm_W2.0mm_P5.00 mm 100nF polyester	3	< 1 €	< 1 €
> C5, C6	Capacitor_THT:CP_Radial_D5.0mm_P2.50 mm 10nF polyester	2	< 1 €	< 1 €
C7	Capacitor_THT:C_Rect_L7.0mm_W2.0mm_P5.00 mm 10pF ceramic	1	< 1 €	< 1 €
D1	BPW21R	1	12 €	12 €
D2	Schottky Diode SD103C	1	< 1 €	< 1 €
> J1, J2	Connector_JST:JST_XH_B2B-XH-A_1x02_P2.50mm_Vertical	2	< 1 €	< 1 €
> R1, R2	Resistor_THT:R_Axial_DIN0207 value 10 k ohm 5 % 1/4w	2	< 1 €	< 1 €
R3	Resistor_THT:R_Axial_DIN0207 330 kohm 1 % 1/4W	1	< 1 €	< 1 €
U1	LM7805 TO-220-3_Horizontal_TabDown	1	1.5 €	1.5 €
U2	OpAmp OP37G DIP-8_W7.62 mm	1	5.5 €	5.5 €

Additional material

Used with	Component	Number	Cost per unit-currency	Total cost-currency
VISTO-Shield	Arduino Mega 2560Rev3 board	1	15 €	15 €
VISTO-Shield	Hitachi HD44780 LCD display	1	3.5 €	3.5 €
VISTO-Shield	CONN HEADER VERT 16POS 2.54MM	1	< 1 €	< 1 €
VISTO-Shield	8PIN 2.54 mm Single Row Female Long pins 11 mm	4	< 1 €	< 1 €
VISTO-Shield	10PIN 2.54 mm Single Row Female Long pins 11 mm	1	< 1 €	< 1 €
VISTO-Shield	DB 25 Parallel port connector male plug	1	< 1 €	< 1 €
VISTO-Shield	2 Core 24 AWG cable	1 m	< 1 €	< 1 €
VISTO-Shield	CONN RCPT HSG 2POS 2.50MM* *needs Crimping Pliers 28–20 AWG JST-XH compatible	2	< 1 €	< 1 €
VISTO-Shield	CONN SOCKET 22-28AWG CRIMP TIN	4	< 1 €	< 1 €
VISTO-light_sensor	2 Core 24 AWG cable	1 m	< 1 €	< 1 €
VISTO-light_sensor	CONN RCPT HSG 2POS 2.50MM*	2	< 1 €	< 1 €
VISTO-light_sensor	CONN SOCKET 22-28AWG CRIMP TIN	4	< 1 €	< 1 €
VISTO-light_sensor	9 V Battery	1	< 1 €	< 1 €
VISTO-light_sensor	9 V Battery Clip Connector	1	< 1 €	< 1 €
VISTO-light_sensor	electronics ABS box min size 53 mm × 30 mm	1	< 1 €	< 1 €
VISTO-light_sensor	Light-shielded container	1	< 1 €	< 1 €

Build instructions

Illustrations of VISTO 2.0, both in its main components and in-situ during measurement, are reported in Fig. 1. VISTO 2.0 is based on the Arduino Mega 2560 Rev3 board [10], which acquires signals from its analog input ports. VISTO 2.0 comprises two units: the main VISTO 2.0 unit (Design file 1), and the light sensor unit comprising a 9 V battery (Design file 2). A two-core 26AWG cable connects the output of the light sensor device to the A0 Arduino analog pin. All connections are indicated in Design files 1–2. Each project contains a Gerber folder, which is ready to be sent to a printed circuit board (PCB) manufacturer. Additionally, in the main unit, a 16 Pin Male Connector must be soldered on the LCD, and attached to the main VISTO 2.0 unit to the J1 LCD_16x02 connector (Design File 1).

In the light sensor unit, the BPW21R photodiode is inserted in a light-shielded container. This container has an open side which will be attached to the monitor, while all other sides will be opaque and must avoid that external light hits the photodiode. The position of the sensor relative to the container, and the container relative to the monitor, remain fixed throughout all the measurement session, thus allowing for replicable measurements if the same stimulus is repeated (Fig. 1). The Feedback Resistor (Rf) of 330Kohm which is used in the light sensor unit gives a correct range of voltage for the LCD monitors tested with the BPW21R photodiode. For a BPW21R sensor with 9 nA/lux, a circuit with feedback resistance of the OpAmp set at 330 kOhm, and Arduino maximum voltage set at 1.1 V, the nominal luminance range is zero to 370 lux. This range is sampled at 8 bit (256 steps), for an actual nominal resolution of 1.45 lux. However, there is a remarkable variability in the sensitivity range of the BPW21R, from 4 to 10 nA/lux [9], and if a researcher is interested to know the luminance range (in lux) of VISTO it is advisable that the sensitivity is calculated for the specific hardware used, according to the formula:

$$\mathrm{Lux} = \mathrm{ArduinoInputVoltage}/\mathrm{FeedbackResistance}/\mathrm{SensorResolution}$$

where Arduino input voltage can be set by software and is set here to 1.1 V, feedback resistance in the present circuit is 330 kOhm, and the nominal sensor resolution for the present BPW21R sensor is 9 A/lux.

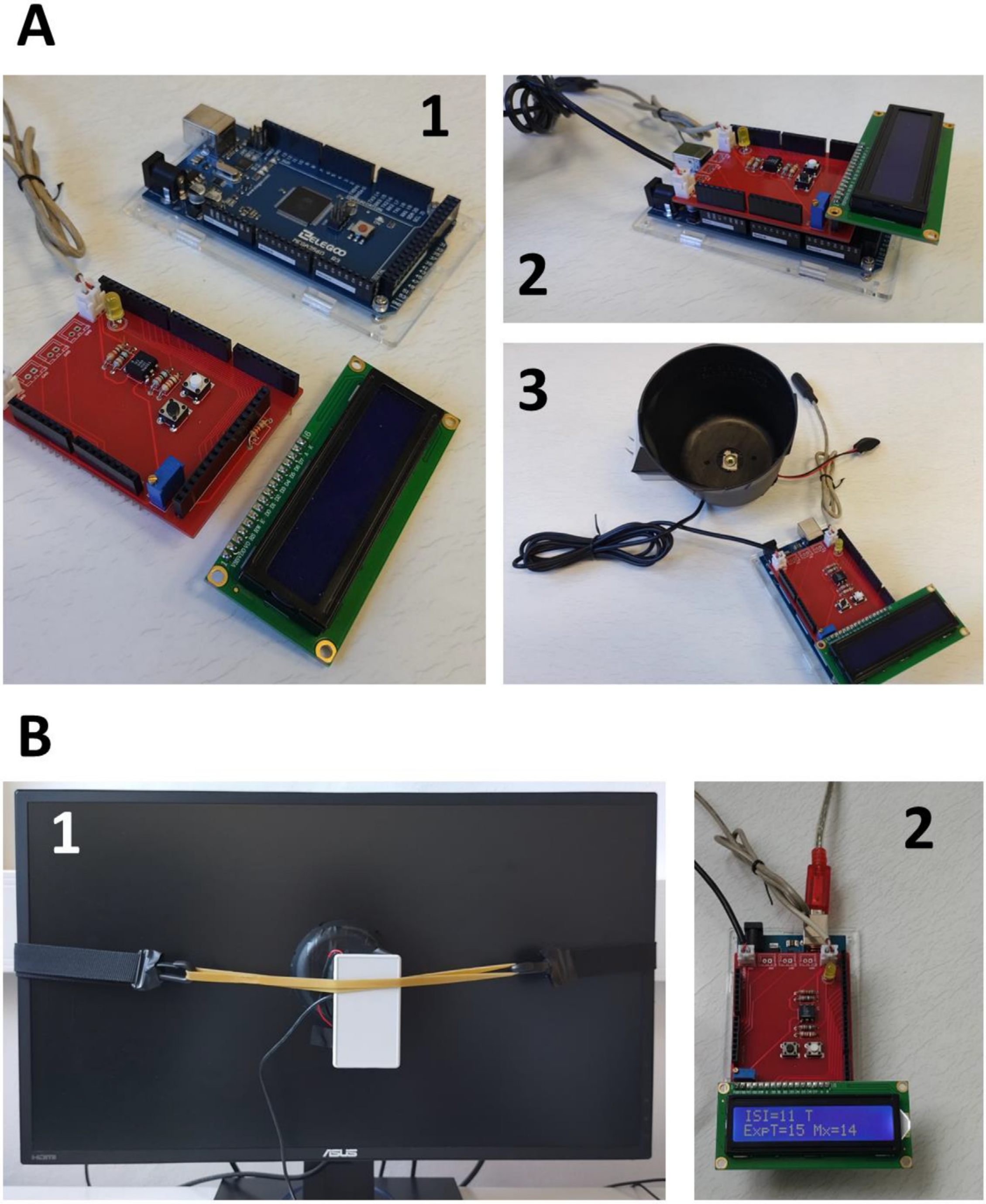

Fig. 1. Visto overview. VISTO 2.0 during assembly and in situ while measuring. Panel A: In 1) the main components of VISTO are visible, which are later assembled into a 2) complete Arduino device and 3) connected to the sensor unit. Panel B: VISTO 2.0 positioned onscreen in the setting phase which is done prior to running an experiment, and temporal parameters ("Timing" Arduino sketch) shown while running.

The external unit (Design file 2) is powered through a 9 V battery aimed at enhancing the signal-to-noise ratio, and includes a transimpedence circuit using an OpAmp OP37 [9] and an LM7805 which stabilizes voltage supply. A minimum of 7 V power to the LM7805 is necessary for the function of the light sensor unit, and a Schottky Diode SD103C protects against accidental battery reversal.

The VISTO 2.0 main unit comprises the Arduino Mega 2560 and Arduino shield with buttons to calibrate the software with the dark and bright color range for the monitor under examination, and an LCD display to visualize timing and luminance information while an experiment is running. VISTO 2.0 acquires the signal though an A/D port (analog pin 0) set by software settings at 0–1.1 V range and digitized at 8 bit precision. Each AD unit corresponds to 4.3 mV. To receive the triggering signal which marks the beginning of a trial, the Arduino board is connected to a parallel port male plug through an 4N35 Opto-isolator, to acquire marker signal from a parallel cable while protecting against incoming signal larger than 5 V, and to eliminate background noise. Connections are: parallel port pin 2 to trigger connector pin 1 (Arduino digital pin 2), parallel port pin 25 (ground) to trigger connector pin 2 (Arduino ground).

Operation instructions

VISTO 2.0 can work in two modalities, namely an epoched recording "temporal profile" modality which is started by a parallel port trigger, and a "timing" modality in which the relative timings of darker patches, lighter stimuli, and parallel triggers are presented on the LCD screen. The modality selection is done by loading the appropriate Arduino sketch (Profile_v22.02.ino or Timing_v22.02.ino; https://doi.org/10.17605/OSF.IO/4B7C5).

Prior to the timing measurement, a scaling must be carried out to adjust the thresholds to the actual high and low luminosity values of each monitor. Differently to the previous VISTO version, the light sensor unit using the BPW21R photodiode and the Operational Amplifier OP37 does not need resistance adjustments for LCD monitors. Scaling is simply done by displaying a black screen and pressing the black button to acquire luminance values for black on the experimental monitor. After scaling is done for darker stimuli, the experimenter can proceed with the scaling for lighter stimuli, which is done by presenting a white screen and pressing the white button to acquire luminance values for the lighter stimuli. After scaling is done, threshold for detecting the onset of a visual stimulus is automatically set at 10 % of the difference between black and white values. During scaling, minimum and maximum luminance values (AD units) are displayed on the VISTO 2.0 LCD display for the black and white patch. As the output of VISTO 2.0 depends on the position of the sensor within the container, on the width of the container, and on the distance between the sensor and the monitor, it is not possible to convert VISTO 2.0 output values to luminance values. Therefore, it must be noted that outputs are in arbitrary AD units. However, due to the stable position of the sensor within the container and the linear response of the sensor and the circuit, VISTO 2.0 data are highly consistent with the measurement of a validated instrument that measures monitor luminance (Gossen MAVO-MONITOR USB; https://gossen-photo.de/en/mavo-monitor-usb/) as reported in Fig. 2.

When working in "temporal profile" modality, luminance samples are sent to the USB serial port at 4000 Hz, in AD units, for epochs of 2000 samples (500 ms).

When working in "timing" modality, the LCD displays:

- ISI value: the timing (in ms) between the offset of the last stimulus, and the onset of the new stimulus. In the case of a trial which is started by a parallel port trigger signal, the delay between the trigger and the onset of the visual signal is reported (in ms), followed by a T character.

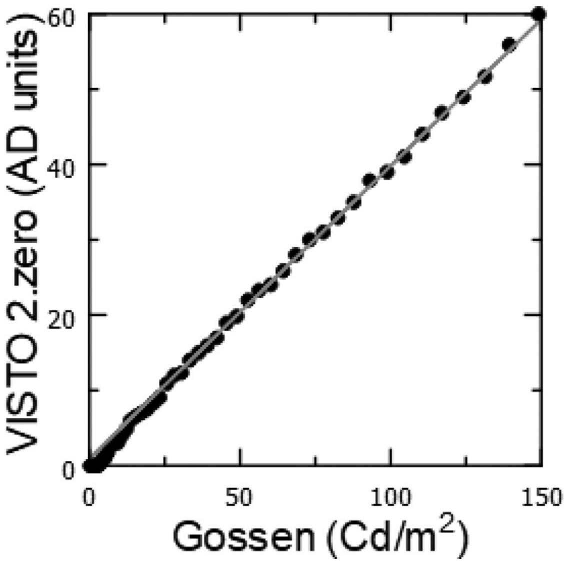

Fig. 2. Luminance measurement. Luminance measurement by VISTO 2.0 and by Gossen MAVO-MONITOR USB for a range of patches ranging from black (RGB average brightness = 0) to white (RGB average brightness = 255). Each point corresponds to a brightness level, and the interpolation line is the best-fitting linear function.

- ExpT: exposure time (in ms) of the visual stimulus, calculated as the absolute difference between the time when the luminance profile first exceeds the 10 % white-black threshold, and when it falls below the same threshold at the end of stimulus presentation.
- Mx: Maximum luminance (AD units) during the peak of the luminance profile, calculated using a smoothed 5-points moving average.

If connected to a USB serial port with 1,000,000 bts, VISTO 2.0 outputs the following values, which can be used to further characterize the luminance profile (see Fig. 3 for specification of the labeling of visual events):

- timeISI_us: the ISI value displayed on the LCD screen, in microseconds
- timeStim_us: the exposure time value displayed on the LCD screen, in microseconds
- blackEnd_us: absolute time of the moment when the luminance profile exceeds the 10 % threshold, in microseconds;
- whiteStart_us: absolute time of beginning of peak signal (exceeding the 90 % of black-white difference), in microseconds;
- whiteEnd_us: absolute time of ending of peak signal (falling below the 90 % of black-white difference), in microseconds;
- blackStart_us: absolute time of the moment when the luminance profile falls below the 10 % threshold, in microseconds;
- blackEnd_ua, whiteStart_ua, whiteEnd_ua, blackStart_ua: luminance values (in AD units) of each event;
- max_ua: maximum luminance value (in AD units) of the stimulus, as displayed on the LCD screen;
- trigger_us: timing of the trigger signal, if present, in microseconds;
- transmissionEnd_us: time of ending of data transmission on the serial port. A minimum of 10 ms is required between two successive stimuli, to allow for data transmission.

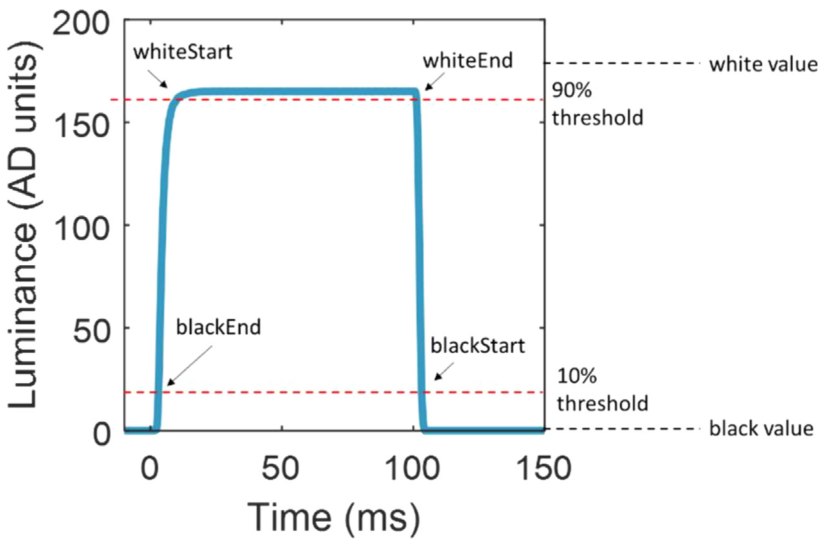

Fig. 3. Profile description. Labeling of visual events in the luminance profile.

The thresholds of 10 % above black and below white values are arbitrary, and can be changed by modifying line 539 of Arduino file *Timing_v22.02.ino*:

$$threshold = (byte)((float)(whiteRef[0] - blackRef[1]) * .1);$$

from .1 (default value) to a higher or lower value; please note that arduino samples luminance at 8bit (256 samples), which gives a limited space for changing the threshold value.

Validation and characterization

VISTO 2.0 was validated here by presenting stimuli that could either be natural scenes, or white patches. Visual stimuli could be presented for a variable amount of time from 16.7 to 100 ms, and VISTO 2.0 was used to measure luminance and timing of the presented stimuli.

Stimuli

A total of 576 pictures were selected from the Internet for the present study, which was used in previous studies on the categorization of natural scenes [11,12]. Each picture portrayed either animals or vehicles, in indoor or outdoor scenarios. Pictures were in color, were resized to 431 × 323 pixels, and were balanced for brightness and contrast (picture brightness M = 127.5, SD = 4.52). Stimuli were presented with PST Software E-Prime 2.0 [13] on a 21" experimental monitor (ViewSonic XG2530) at 1024x768 pixel resolution.

Procedure

Stimulus presentation is displayed in Fig. 4. Each visual stimulus was presented along with a trigger signal delivered through the parallel port. Pictures were presented for a variable time between 16.67 and 100 ms (16.67, 33.33, 50, 66.67, 87.33, 100), corresponding to the exposure times resulting from an LCD computer screen set at 60 Hz refresh rate. The experiment comprised the presentation of the whole set of 576 pictures in all exposure times, followed by the presentation of an equal number of white patches (RGB 255, 255, 255) in the same exposure times, for a total of 6912 trials.

The light sensor of VISTO 2.0 was positioned centrally on the picture, in order to cover an area corresponding roughly to a foveal fixation. For each image, we measured onset time, exposure time and maximum luminance, calculated as the maximum value observed in a 2 ms (5 samples) moving average time interval once a stimulus was detected (see Fig. 3).

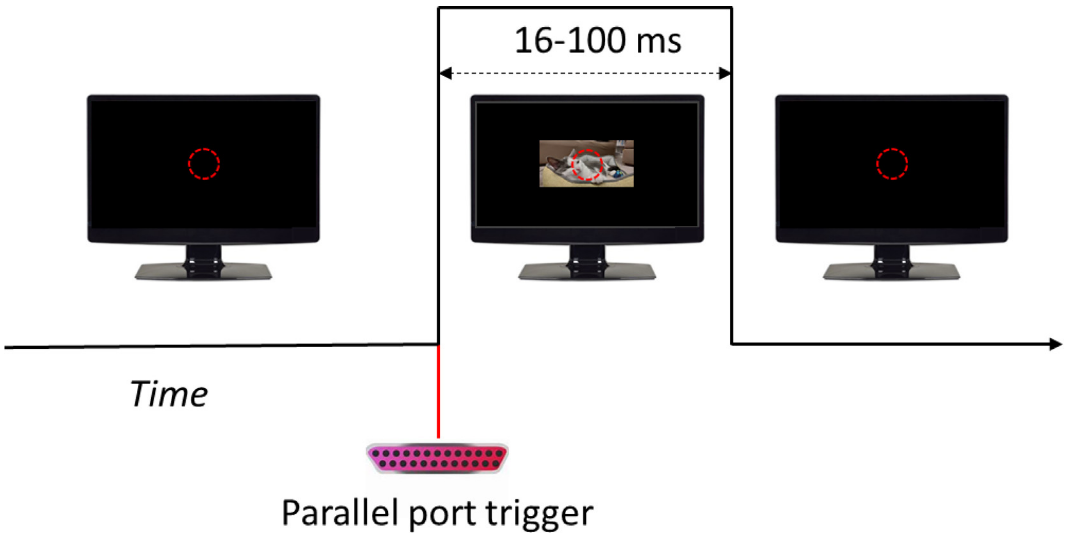

Fig. 4. Procedure. Procedure for presentation of marker stimulus (parallel port signal) and visual stimulus. Red dashed circle represents the area covered by the photodiode. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Results

Luminance

Luminance profiles are reported in Fig. 5. As expected, exposure time increased with programmed time (from 16.67 to 100 ms), and the luminance of white patches (full brightness) was higher compared with that of natural scenes. In terms of timing, the luminance profile increased linearly from the intertrial black value to the maximum plateau that was reached when each stimulus was presented (Fig. 5). Moreover, natural scenes had a high variability in terms of luminance (shaded area in Fig. 5), while white patches had almost no variability. Importantly, this variability resulted from the presentation of different images; variability for repeated presentations of the same picture was low (standard deviation for ten presentations, averaged across all images = 0.40, CI 0.34 to 0.36), and was only slightly higher than variability for white patches (standard deviation = 0.29). On the other hand, variability for different pictures within each exposure time was remarkably higher (standard deviation, averaged across all presentation times = 20.87, CI = 12.35 to 29.39), which was remarkably higher than variability for white patches (standard deviation = 0.09).

Focusing on trials in which stimulus luminance exceeded the minimum threshold (17 AD units, resulting from the 10 % of the difference between black, which was 2, and white, which was 172, scaling values), we calculated maximum luminance and timing for each trials; all other trials, which did not exceed the minimum threshold were marked as missed. Only three trials from the natural scenes pool were missed. The luminance of detected stimuli is reported in Fig. 6 and Table 1. Again,

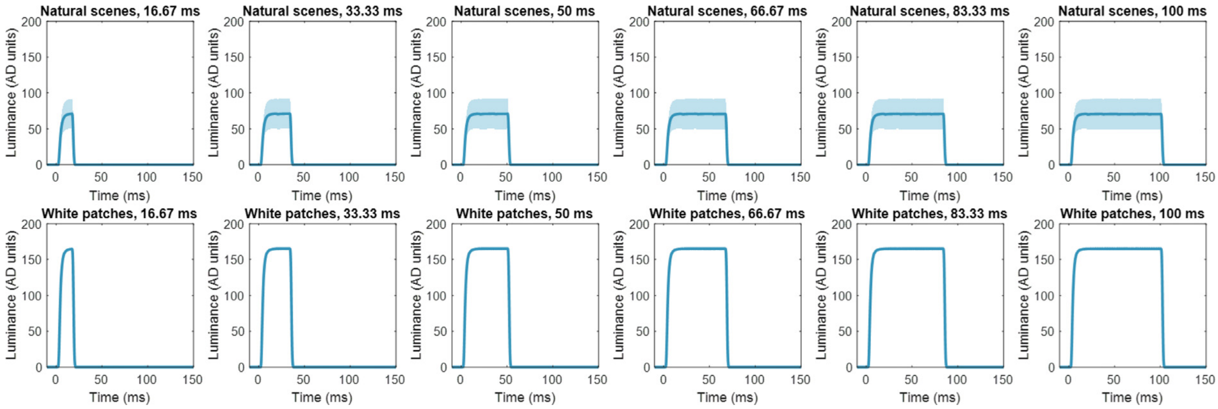

Fig. 5. Luminance Profiles. Luminance profile for natural scenes and white patches, separately for each exposure duration. Shaded areas represent standard deviations.

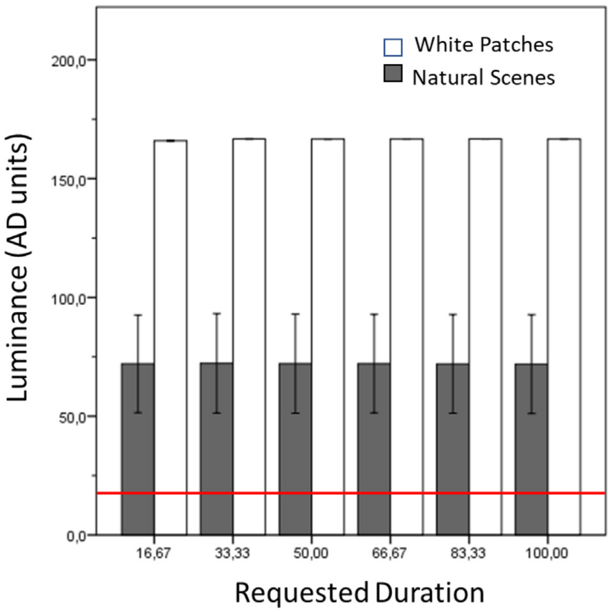

Fig. 6. Maximum Luminance. Luminance values for natural scenes and white patches, separately for each exposure duration. Error bars represent standard deviations.

Table 1
Luminance of natural scenes and white patches. For each parameter, average of 1000 bootstrap samples and 95% confidence intervals are reported.

	Mean						Standard Deviation					
	Natural Scenes			White Patches			Natural Scenes			White Patches		
Stimulus Duration	Average	-CI	+CI	Average	-CI	+CI	Average	-CI	+CI	Average	-CI	+CI
16.67	72.03	70.42	73.70	165.95	165.93	165.97	20.55	19.47	21.61	0.23	0.22	0.24
33.33	72.26	70.64	74.09	166.70	166.69	166.71	20.95	19.86	21.91	0.13	0.12	0.14
50	72.13	70.38	73.72	166.64	166.63	166.64	20.88	19.88	21.89	0.06	0.06	0.07
66.67	72.12	70.45	73.88	166.63	166.63	166.63	20.71	19.70	21.73	0.02	0.01	0.02
83.33	71.99	70.19	73.67	166.65	166.65	166.65	20.77	19.70	21.74	0.02	0.01	0.03
100	71.94	70.21	73.52	166.63	166.63	166.64	20.79	19.64	21.80	0.08	0.07	0.09

Fig. 7. Picture examples. Example of pictures which had the lowest and highest luminance value, measured in the center of the picture.

while natural scenes had a high variability, white patches had an extremely low variability. Fig. 7 reports some examples of stimuli with the lowest and highest luminance.

Timing

Onset times are reported in Table 2 and Fig. 8. Although parallel trigger and stimulus onset were programmed to be simultaneous, a systematic delay of about 16 ms was observed for both white patches and natural scenes, indicating that

Table 2
Onset times of natural scenes and white patches. For each parameter, average of 1000 bootstrap samples and 95% confidence intervals are reported.

	Mean						Standard Deviation					
	Natural Scenes			White Patches			Natural Scenes			White Patches		
Stimulus Duration	Average	-CI	+CI	Average	-CI	+CI	Average	-CI	+CI	Average	-CI	+CI
16.67	17.12	17.08	17.17	16.46	16.44	16.47	0.55	0.34	0.80	0.15	0.14	0.15
33.33	17.05	17.00	17.11	16.42	16.41	16.43	0.65	0.34	1.01	0.15	0.14	0.15
50	17.03	16.99	17.09	16.40	16.39	16.41	0.69	0.34	1.08	0.14	0.14	0.15
66.67	16.99	16.96	17.02	16.39	16.38	16.40	0.36	0.33	0.39	0.14	0.14	0.15
83.33	16.97	16.95	17.00	16.38	16.37	16.39	0.35	0.32	0.38	0.14	0.14	0.15
100	16.97	16.94	17.00	16.38	16.37	16.39	0.36	0.33	0.39	0.14	0.14	0.15

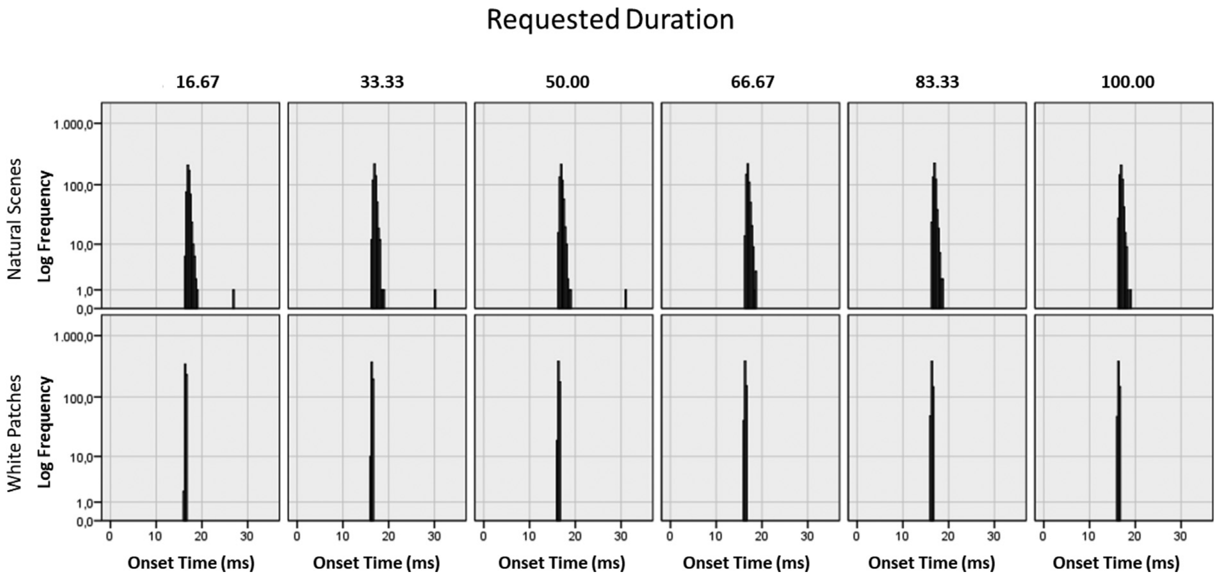

Fig. 8. Onset times. Distribution of onset times, for each requested duration and stimulus type.

one frame was lost because of presentation computer delays, or monitor response. In addition to this, natural scenes had a wider distribution of values, and onsets were between 16.21 and 31.03.

Fig. 9 reports exposure times for white patches and natural scenes. As observed for luminance values, natural scenes have a higher variability compared with white patches. Moreover, while the software log reports a stable exposure time across pictures and natural scenes, actual measurements of exposure times indicated that the exposure time of natural scenes was more variable than that of white patches. Average and standard deviation of exposure time, along with bootstrapped confidence intervals, are reported in Table 3.

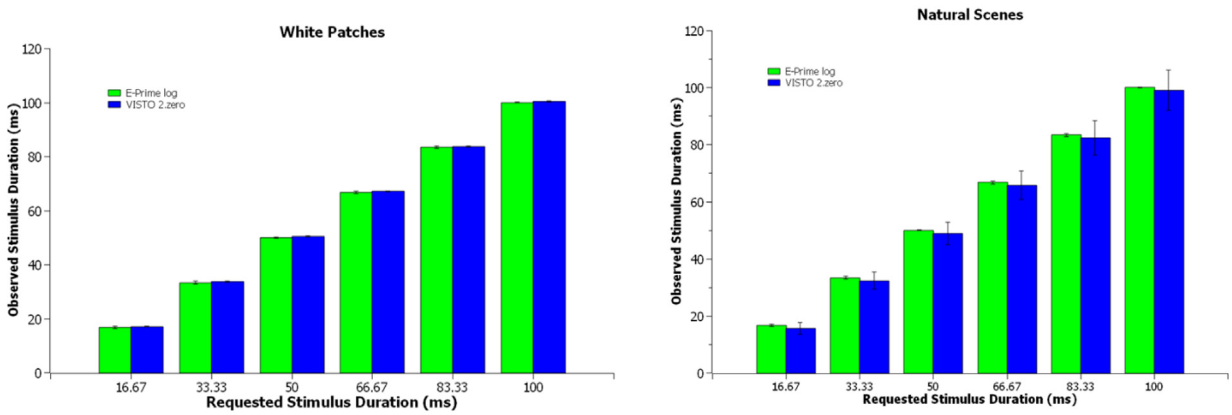

Fig. 9. Exposure times. Exposure times as indicated by VISTO 2.0 and software log, separately for each requested duration and stimulus type.

Table 3
Exposure times of natural scenes and white patches. For each parameter, average of 1000 bootstrap samples and 95% confidence intervals are reported.

	Mean						Standard Deviation					
	Natural Scenes			White Patches			Natural Scenes			White Patches		
Stimulus Duration	Average	-CI	+CI	Average	-CI	+CI	Average	-CI	+CI	Average	-CI	+CI
16.67	15.60	15.53	15.67	17.01	17.01	17.02	0.82	0.64	1.07	0.08	0.05	0.09
33.33	32.30	32.17	32.39	33.72	33.70	33.74	1.41	0.64	2.26	0.25	0.25	0.25
50	48.91	48.73	49.03	50.36	50.35	50.38	2.04	0.62	3.41	0.22	0.21	0.23
66.67	65.67	65.62	65.73	67.03	67.02	67.04	0.65	0.60	0.70	0.12	0.10	0.13
83.33	82.34	82.28	82.39	83.69	83.67	83.71	0.65	0.60	0.70	0.24	0.24	0.25
100	99.01	98.95	99.06	100.34	100.32	100.36	0.65	0.60	0.69	0.23	0.22	0.24

Discussion

Here, we presented an improved method for determining the temporal luminance profile and timing of visual stimuli, and examined its application to the presentation of simple stimuli (white patches) and complex ones (natural images). Stable results which were comparable both with software logs and with the original VISTO [5] were observed for white patches. However, when presenting natural scenes, the variability in scene composition determined different luminance slopes, which resulted in larger variability not only in terms of maximum luminance, but also of onset and exposure time. This variability was largely related to changes in picture content, rather than to the repeated presentation of the same pictures, supporting the use of VISTO 2.0 prior to the actual running of an experiment, during the fine-tuning of the experimental setup. The variability in maximum luminance values depends on the position of the sensor, relative to the composition of each picture; if a picture has a lighter central area, and the sensor is placed centrally, the output will reveal a high luminance, while the opposite will happen for pictures with a central dark area (Fig. 7). Similarly in a typical experiment with human participants, the response to the brightness of the scene (e.g., the pupillary light reflex) depends both on participant's gaze, and on picture composition.

Here, we observed that in addition to maximum luminance, also onset and offset times varied among natural images. Variations in exposure time and in onset time have detrimental effects on the possibility to observe visual phenomena related with perception, cognition, or emotion [14–21]. Moreover, unpredictable onsets reflect on any measure that relies on the averaging of several epochs, such as ERPs [22], resulting in smeared and less temporally precise averages.

An additional issue that was examined here, relying on the better signal-to-noise ratio and the BPW21R photodiode, is the impact of image variability on the temporal luminance profile. We observed that differences in picture composition reflected not only on luminance, but also (although to a limited extent) on the onset and exposure time of natural scenes. As several studies rely on the investigation of what can be acquired by a very short exposure (e.g., [7,23]), it is critical that experimenters can control that the actual timing corresponds to the programmed one. Here, we showed that while the software log reported regular behavior during visual presentation, actual recording on the LCD monitor indicted that exposure time of natural scenes varied.

In terms of future developments, this same device will be extensible to other visual presentation hardware, as well to more sensory modalities. In terms of extending VISTO to other visual presentation hardware, such as HDR monitors [24] it would be desirable to increase resolution. As resolution depends on the feedback resistance to the OpAmp, it might me increased by increasing the resistance value; however, an important limitation in this sense is given by the 8bit sampling of Arduino, which only allows for 256 levels of luminance. The described version of VISTO has a modular design, which comprises a main unit and an external sensor. While we used VISTO 2.0 to measure visual stimuli, the main unit can be used to acquire signal by external sensory units that provide a continuous signal within the Arduino analog port range. In the future, other external sensors comprising, e.g., acoustic or piezoelectric sensors, can be developed and connected to the presented device.

Ethics statements

This work did not involve neither animal nor human subjects.

CRediT authorship contribution statement

Andrea De Cesarei: Conceptualization, Methodology, Software, Validation, Formal analysis, Resources, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Michele Marzocchi:** Methodology, Software, Validation, Investigation, Data curation, Writing – original draft, Writing – review & editing. **Maurizio Codispoti:** Conceptualization, Resources, Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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