

## Basic Neuroscience

## An inexpensive Arduino-based LED stimulator system for vision research

Petteri Teikari<sup>a,b,\*</sup>, Raymond P. Najjar<sup>a,b,2</sup>, Hemi Malkki<sup>c,3</sup>, Kenneth Knoblauch<sup>a,b,4</sup>,  
Dominique Dumortier<sup>d,5</sup>, Claude Gronfier<sup>a,b,\*,1</sup>, Howard M. Cooper<sup>a,b,\*,\*,1</sup>

<sup>a</sup> Stem Cell and Brain Research Institute, INSERM U846, 18 avenue Doyen Lépine, 69500 Bron, France

<sup>b</sup> Université Claude Bernard, Lyon I, Lyon, France

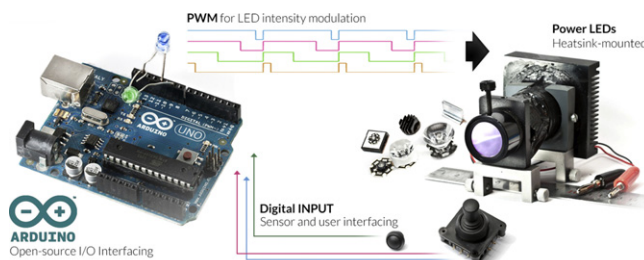
<sup>c</sup> Cognitive and Systems Neuroscience, Center for Neuroscience, Swammerdam Institute for Life Sciences, University of Amsterdam, PO 94232, 1090 GE Amsterdam, The Netherlands

<sup>d</sup> École Nationale des Travaux Public de l'Etat, LASH, DGCB, Rue Maurice Audin, 69518 Vaulx-en-Velin, France

## HIGHLIGHTS

- ▶ We propose an inexpensive system to control light intensity for research applications in vision research.
- ▶ The system is based on light emitting diodes (LEDs) and open-source Arduino microcontroller.
- ▶ The visual stimulator has been used in applications including rodent pupillometry, cognitive learning, and human psychophysics.
- ▶ Applications that can be easily implemented for students, educational purposes and universities with limited resources.

## GRAPHICAL ABSTRACT



## ARTICLE INFO

## Article history:

Received 24 June 2012

Received in revised form

11 September 2012

Accepted 13 September 2012

## Keywords:

LED  
Arduino  
Visual stimulator  
Microcontroller  
Pupillometry  
Education

## ABSTRACT

Light emitting diodes (LEDs) are being used increasingly as light sources in life sciences applications such as in vision research, fluorescence microscopy and in brain–computer interfacing. Here we present an inexpensive but effective visual stimulator based on light emitting diodes (LEDs) and open-source Arduino microcontroller prototyping platform. The main design goal of our system was to use off-the-shelf and open-source components as much as possible, and to reduce design complexity allowing use of the system to end-users without advanced electronics skills. The main core of the system is a USB-connected Arduino microcontroller platform designed initially with a specific emphasis on the ease-of-use creating interactive physical computing environments. The pulse-width modulation (PWM) signal of Arduino was used to drive LEDs allowing linear light intensity control. The visual stimulator was demonstrated in applications such as murine pupillometry, rodent models for cognitive research, and heterochromatic flicker photometry in human psychophysics. These examples illustrate some of the possible applications that can be easily implemented and that are advantageous for students, educational

\* Corresponding author at: Stem Cell and Brain Research Institute, INSERM U846, 18 avenue Doyen Lépine, 69500 Bron, France. Tel.: +33 04 72 91 34 68; fax: +33 04 72 91 34 61; mobile: +33 48 5 3659 1402.

\*\* Corresponding author at: Stem Cell and Brain Research Institute, INSERM U846, 18 avenue Doyen Lépine, 69500 Bron, France. Tel.: +33 04 72 91 34 89; fax: +33 04 72 91 34 61.

\*\*\* Corresponding author at: Stem Cell and Brain Research Institute, INSERM U846, 18 avenue Doyen Lépine, 69500 Bron, France. Tel.: +33 04 72 91 34 69; fax: +33 04 72 91 34 61.

E-mail addresses: [petteri.teikari@gmail.com](mailto:petteri.teikari@gmail.com) (P. Teikari), [raymond.najjar@inserm.fr](mailto:raymond.najjar@inserm.fr) (R.P. Najjar), [haimalkki@gmail.com](mailto:haimalkki@gmail.com) (H. Malkki), [ken.knoblauch@inserm.fr](mailto:ken.knoblauch@inserm.fr) (K. Knoblauch), [dominique.dumortier@entpe.fr](mailto:dominique.dumortier@entpe.fr) (D. Dumortier), [claudie.gronfier@inserm.fr](mailto:claudie.gronfier@inserm.fr) (C. Gronfier), [howard.cooper@inserm.fr](mailto:howard.cooper@inserm.fr) (H.M. Cooper).

<sup>1</sup> Co-senior authors.

<sup>2</sup> Tel.: +33 04 72 91 34 68; fax: +33 04 72 91 34 61.

<sup>3</sup> Tel.: +31 447 804 340 593.

<sup>4</sup> Tel.: +33 04 72 91 34 77; fax: +33 04 72 91 34 61.

<sup>5</sup> Tel.: +33 04 72 04 70 87; fax: +33 04 72 04 70 41.

purposes and universities with limited resources. The LED stimulator system was developed as an open-source project. Software interface was developed using Python with simplified examples provided for Matlab and LabVIEW. Source code and hardware information are distributed under the GNU General Public Licence (GPL, version 3).

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## 1. Introduction

Light-emitting diodes (LEDs) have become more and more common as a low-cost and flexible way to provide light stimuli in vision research (Nygaard and Frumkes, 1982; Scholfield and Murdock, 1987; Watanabe et al., 1992; Pokorny et al., 2004; Fadda and Falsini, 1997; Demontis et al., 2005; da Silva Pinto et al., 2011; Rogers et al., 2012). LEDs offer easier and more versatile control of light characteristics (Schubert and Kim, 2005) compared to traditional light sources such as xenon, mercury, metal halide and halogen lamps which often require various auxiliary devices in experimental settings such as a set of filters for spectral tuning and shutters to control exposure duration. LEDs are close to being monochromatic light sources (half-bandwidths of 20–30 nm) and they provide roughly linear light output (Svilainis, 2009) in response to pulse-width modulation [PWM, Narra and Zinger, 2004] control signal over an extended dynamic range. The response time of LED chips itself is very fast (in the order of nanoseconds). The whole system response of the LED driver and the LED chip together is slower, but still sufficient for most purposes, the response time being in the order of microseconds (Albeanu et al., 2008).

An additional advantage of LEDs is their characteristic low electromagnetic interference (EMI) emission (Svilainis, 2012), as compared to cathode ray tube (CRT) monitors that can cause significant electromagnetic interference to electrical cables (Hogg, 2006), making them especially suitable to be used with electrophysiological techniques such as electroretinography [ERG, Fadda and Falsini, 1997], magnetoencephalography [MEG, Wilson et al., 2009], and electroencephalography [EEG, da Silva Pinto et al., 2011] in which the physiological potentials are typically very weak and are prone for artifacts.

LEDs are typically controlled with a discrete on–off PWM signal, in which the on-time (duty cycle) is in theory linearly proportional to the light output. More detailed discussion on the advantages of LEDs over traditional light sources can be found in regard to the noise and stability characteristics (Brophy, 1967; Rumyantsev et al., 2004; Salzberg et al., 2005), and to biological applications such as in widefield microscopy (Holman, 2007) and visual neuroscience (da Silva Pinto et al., 2011).

Despite the widespread use of LEDs in scientific research, there is only a handful of papers dedicated to the design of LED stimulators for research purposes (Watanabe et al., 1992; Pokorny et al., 2004; Fadda and Falsini, 1997; Demontis et al., 2005; Nishimura et al., 2006; Albeanu et al., 2008; da Silva Pinto et al., 2011; Rogers et al., 2012). Additionally, the existing approaches have relied on either off-the-shelf proprietary laboratory equipment (e.g. Fadda and Falsini, 1997), or advanced electronics from the end-users (e.g. Watanabe et al., 1992; Demontis et al., 2005). da Silva Pinto et al. (2011) recently described an open-source portable LED stimulator promoting the reproducibility of their device by providing the hardware schematics, layouts, parts lists and application source freely on their support website (<http://sites.google.com/site/mculedstimulator/>), the cost of their hardware parts being around \$100 (~76€).

However, based on our experience the described implementation of a LED stimulator might be technically too challenging for vision research laboratories without staff with good electronics and programming skills. We sought to simplify the design and propose an even simpler and low cost alternative for the

design of da Silva Pinto et al. (2011) using the open source electronics prototyping platform Arduino [<http://arduino.cc/>], for an in-depth review of the technology see Wheat (2011), and for applications and programming see Margolis (2011)] which is based on flexible, easy-to-use hardware and software. There is a lively community of Arduino users contributing and benefiting from their collective research (see Arduino Playground for example, <http://arduino.cc/playground/>).

Arduino has been employed in scientific applications such as LED light control of an open-source *in vivo* multispectral imaging system for rodents (Sun et al., 2010), teaching violin bowing by providing an interface for combining motion sensing and vibrotactile feedback (van der Linden et al., 2011), smart textile design with optical fiber integration to clothes (Parkova et al., 2011), wearable computing (Buechley and Eisenberg, 2008; Itoyama et al., 2011), and in cross-disciplinary teaching of biology and computer science (Grasel et al., 2010).

Following the example set by da Silva Pinto et al. (2011), we provided all the hardware designs and application source code freely on our project website <http://code.google.com/p/arduino-v-neusci/> distributed under the GNU General Public License (GPL, version 3, <http://www.gnu.org/copyleft/gpl.html>).

## 2. Materials and methods

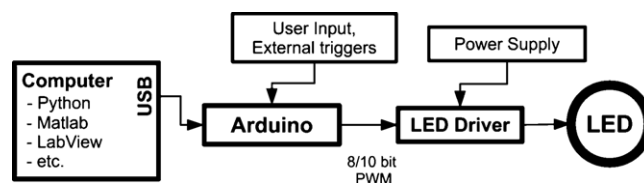
### 2.1. Design of the LED stimulator

#### 2.1.1. Overview

The LED stimulator is designed around the Arduino prototyping microcontroller platform (or other Arduino-compatible boards such as the Maple®) consisting of five components: a computer with chosen programming environment, the Arduino prototyping platform, the constant-current LED driver, the LED itself, and a power supply (Fig. 1).

The computer is used for online control of the light intensity, either setting the light intensity manually by the experimenter or making the light intensity depend on the subject input (e.g. if the subject of the experiment controls the light intensity with a joystick) or some external trigger such as some other stimulus presentation or sensor reading.

The Arduino is used in analogous fashion to a data acquisition device [DAQ, see for example Stankus et al., 2010] to read analog/digital inputs from external switches, buttons, joysticks,



**Fig. 1.** Block diagram of LED driving scheme. Simple scheme of computer-controlled LED driving with Arduino, default mode of 8-bit PWM output allowing roughly the dynamic range of 2 log units ( $2^8$  intensity levels). The Arduino can be interfaced via various programming environments and languages, and then programmed via USB interface. The Arduino can be either powered by the USB interface or with an external power supply or a battery. The LED driver should have an option to be controlled via PWM control signal, otherwise the components can be chosen from vast number of commercial solutions.

sensors, etc. [see for example D'Ausilio, 2011], and providing PWM signal out to control the LED drivers.

The maximum current of the PWM output of the Arduino Uno used in this study is only 50 mA whereas typical high-power LEDs can be driven with currents ranging from 350 mA up to several amperes. The use of proprietary LED driver makes the system more modular, allowing the stimulator system to be equipped with the most suitable LED driver for the desired application. Most LED drivers in the market are designed to produce constant-current output for driving LEDs in contrast to previous voltage-controlled schemes with complex feedback circuits (Watanabe et al., 1992).

The modular interface between the LED driver and the LED in practice means that the LED can be chosen freely from available options ensuring that the LED can withstand the maximum current of the LED driver. The power supply can be then any 5 V<sub>DC</sub> source preferably a battery or linear power supply to minimize the possible electromagnetic interference from switched power supplies. Additionally, exactly the same PWM-based driving scheme is used for electrical motors in robotics (Warren et al., 2011), in computer numerical control (CNC) machining (e.g. <http://www.linuxcnc.org/>), in 3D-printing (e.g. RepRap, Jones et al., 2011), and in speed control of DC motors (e.g. <http://arduino.cc/it/Main/ArduinoMotorShieldR3>).

### 2.1.2. Hardware

**2.1.2.1. Microcontroller.** The Arduino Uno is an open-source microcontroller board based on the ATmega328. It has 14 digital input/output pins (of which 6 can be used as PWM outputs) and 6 analog input. It contains everything needed to support the microcontroller, and it can be simply connected to a computer with an Universal Serial Bus (USB) cable to get started. Alternatively, a more advanced implementation Arduino Mega2560 can be chosen with more input/output pins (54 pins compared to 14 pins of Arduino Uno). The design described here is compatible with other Arduino boards including the Arduino Mega2560.

The Arduino Uno can be programmed with the Arduino Integrated Development Environment (IDE) software based on the Processing IDE (<http://processing.org>). The C-based simple program code for the Arduino is referred to as a *sketch*. Collection of sketches for specific functionalities are referred to as *libraries* (<http://arduino.cc/playground/Code/Library>), often simplifying the programming task of the end-user hiding the code inside the libraries ('black box' approach). The Arduino can be programmed within the limitations of the 32 KB memory and the processing power of the microcontroller (Wheat, 2011). Arduino can function autonomously without being connected to a computer, or alternatively programmed to respond mainly to commands sent from the computer via various software interfaces (<http://arduino.cc/playground/Main/InterfacingWithSoftware>) or to the data acquired from the input channels (<http://arduino.cc/playground/Main/InterfacingWithHardware>). Additionally, the Arduino can be programmed and controlled via third-party programming environments such as Sphish (Kato, 2010).

The hardware functionality of Arduino can be extended with external plug-ins referred as *shields* (<http://shieldlist.org>) commercially manufactured or created by the user. The functions of shields include for example adding networking capabilities such as ethernet (<http://arduino.cc/en/Main/ArduinoEthernetShield>), Bluetooth (<http://iteadstudio.com>), ZigBee (<http://arduino.cc/it/Main/ArduinoXbeeShield>); TFT touch panel capability (<http://www.adafruit.com/products/376>); data logging capability without the need of a computer (<http://www.ladyada.net/make/logshield>); joystick and button combination for reading user input (<http://www.sparkfun.com/products/9760>); motor drive shields (<http://arduino.cc/en/Main/Arduino>

[MotorShield](http://arduino.cc/en/Main/Arduino)); and specific shields with LED drivers included for LED control (<http://www.chestersgarage.com>; <http://neuroelec.com/hp-rgb-led-shield>). In practice, the ethernet shield gives the Arduino an IP address allowing it to be controlled over the internet, the Bluetooth shield allows wireless communication with mobile phones running on Android (Amarino project, <http://www.amarino-toolkit.net/>) and iOS/iPhone (e.g. <http://www.sparkfun.com/tutorials/152>), and the ZigBee shield interaction with wireless sensor networks for example Faludi (2010).

As Arduino is released as an open-source hardware project, there are various non-commercial and commercial implementations of the same idea with inter-compatible interfaces. In practice, some of the functions can be stripped out for cheaper or smaller platforms as with Oak Micros om328p (<http://www.arduino.cc/playground/Main/om328p>), or alternatively upgrading some components as for example with the case of Maple Rev. 5 allowing higher PWM resolution and higher PWM frequency. Furthermore some Arduino-compatible modifications are optimized for certain applications as for example for light control (Lighduino, <http://www.toastedcircuits.com/>), Brain-Computer Interfacing (BCI, <http://pceeg.sourceforge.net>), and Global Positioning System (GPS) data logging platform for wireless telemetry (Arduemetry, <http://www.digitalmiser.com/projects/arduemetry/>). Interested readers are referred to the work of Mellis and Buechley (2012) for description of the collaborative modification process of Arduino-compatible boards.

**2.1.2.2. LEDs.** The LED light chips come in various form factors ranging from small surface-mounted devices (SMD) LEDs to larger high-power LED sources that are often mounted on metal bases allowing easy soldering and connection with the heat sink. Recently, solderless LED sockets have been introduced both for high power LEDs (e.g. Molex, <http://www.molex.com/>); Tyco Electronics, <http://www.te.com/catalog/minf/en/763>) and for LED light modules (e.g. Xicato, <http://www.xicato.com/>; Vexica Lumaaura, <http://www.vexica.com/>; Philips Fortimo, <http://www.lighting.philips.com>) making LEDs easier to implement in a research setting.

LED chips are available from various vendors including Cree Inc. (<http://www.cree.com>), LedEngin Inc. (<http://www.ledengin.com>), Nichia (<http://www.nichia.com>), Osram GmbH (<http://www.osram-os.com>), Philips Lumileds (<http://www.philipslumileds.com>), and Seoul Semiconductor (<http://acriche.com>).

Commercial vendors of LED optics for shaping the light beam include Carclo (<http://www.carclo-optics.com>), Dialight (<http://www.dialight.com>), Fraen (<http://www.fraensrl.com>), Khatod (<http://www.khatod.com>), Ledil (<http://www.ledil.fi>), Philips Lumileds (<http://www.philipslumileds.com>), and Polymer Optics Limited (<http://www.polymer-optics.co.uk>).

**2.1.2.3. LED driver.** LED drivers are widely available in roughly three different groups, based on their form factor as for LEDs: (1) the surface-mounted devices (SMD) that are very small (1–3 mm × 1–3 mm) designed for mass produced electronics, (2) the "medium-sized" LED driver requiring either soldering or being supplied with factory-soldered wires, and (3) LED drivers designed for architectural lighting not often requiring any soldering.

The first group of SMD LED drivers offer the most technical flexibility and performance, but can be hard to implement in environments without advanced soldering equipment and staff. Commercial vendors for SMD LED drivers include Analog Devices (<http://www.analog.com>), Diodes Inc. (<http://www.diodes.com>), Infineon Technologies (<http://www.infineon.com>), Maxim



**Table 1**

Cost budget of the system. Update later, just to give view for the reader of the cost of the proposed system which is very low. URL: Uniform Resource Locator.

Component	URL	Cost (€)	Cost (\$)
Arduino Uno or equivalent	<a href="#">URL</a>	~25–50	~33–60
LED Driver (e.g. XP Power)	<a href="#">URL</a>	~13	~17
LED Optics	<a href="#">URL</a>	~1–5	~1.3–6.5
Heat sink	<a href="#">URL</a>	~3.5	~4.6
Thermal adhesive	<a href="#">URL</a>	~10	~13
High-Power LED, Lumiled	<a href="#">URL</a>	~3–7	~3.9–9.2
DC Power Supply (linear)	<a href="#">URL</a>	~10–20	~13–26

(<http://www.maxim-ic.com>), ON Semiconductors (<http://www.onsemi.com>), and Texas Instruments (<http://www.ti.com>).

The second group from which our XP Power (<http://www.xppower.com>) was selected (see Section 2.2.3) provides a compromise between the technical performance in ease-of-use in environment with only basic soldering tools while still providing good solutions for scientific applications. Commercial vendors include, LuxDrive producing BuckPuck (<http://www.luxdrive.com>), and Recom (<http://www.recom-international.com>).

The third group often contain all the accessory electronics around the LED drivers like resistors, capacitors, coils and all the connectors ready assembled. The LED drivers from this group might not be suitable for applications requiring fast response times if they are optimized for architectural lighting with high reactive impedance dampening their response to electromagnetic interference (EMI) emission. Commercial vendors include Integrated System Technologies (<http://www.istl.com>), Osram GmbH (<http://www.osram-os.com>) and Philips (<http://www.advanced.philips.com>).

Special categories of LED drivers include dedicated LED flash circuits mainly used to drive the LED flashes used in camera phones that could be used as well as in scientific applications such as in the flash electroretinogram (Viswanathan et al., 2011), requiring pulsed lights with a lower frequency compared to PWM pulsing. Additionally, Nishigaki et al. (2006) used a custom-built LED driver circuit providing stroboscopic illumination in fluorescent cell imaging in which the reduced light exposure was shown to reduce the phototoxicity of the illuminating light to the imaged cell. Dedicated LED flash circuit manufacturers include among others Analog (e.g. ADP 1650), Maxim (e.g. MAX1583), National Semiconductor (e.g. LM2754), and Texas Instruments (e.g. TPS61310).

Additionally one can search for further information from magazines devoted to LED technology, those including for example LED Professional (<http://www.led-professional.com>), LEDs Magazine (<http://www.ledsmagazine.com>), LED Journal (<http://www.ledjournal.com>), and more general Electronic Engineering Times (<http://www.eetimes.com>).

A cost estimate of the proposed LED stimulator system with exemplary LED components is shown in Table 1.

### 2.1.3. Software

The Arduino needs a sketch to be uploaded via the Arduino IDE, so that Arduino understands the commands sent for example from Python or Matlab code. Software development for Python (version 2.7) and Matlab (version 2011a) presented here was done with Linux Ubuntu 11.04, and the LabVIEW development (Evaluation version of LabVIEW 2011) with Mac OS X 10.6.8.

**2.1.3.1. Arduino sketches.** The LED control was implemented in the Python programming language (<http://www.python.org/>) using Geany (<http://www.geany.org/>) as the integrated development environment (IDE). The choice of Python provided a cost-free way to interact with the Arduino in contrast to the commercial license

required, for example, for Matlab and for LabVIEW. The use of Python facilitates the integration of the Arduino system described here, for example to existing electrophysiological (Spacek et al., 2009) and visual psychophysics (Peirce, 2007) software packages written in Python. The access to Arduino is very straightforward under Unix-systems (Linux, Mac) as it functions as any serial interface device, thus allowing one to read and write to it as if it was a file. Additionally, there is a wrapper library called pySerial (<http://pyserial.sourceforge.net/>) that handles the serial interface between the computer and the Arduino, a library that works across all operating systems.

Additionally to fully open-source Python implementation, LabVIEW virtual instruments (VIs, “LabVIEW programs”) were developed by us (available from: <http://code.google.com/p/arduino-v-neusci/>) to demonstrate simple LED intensity control with PWM along with an implementation of the heterochromatic flicker photometry paradigm (see Section 2.2.3). The VI development was done using the NI LabVIEW Interface for Arduino Toolkit (LIFA, <http://ni.com/arduino>). The LIFA comes with its own Arduino sketch (adiosrv.pde) that need to be uploaded to your Arduino board before running our VIs or the example VIs provided by National Instruments (<http://www.ni.com/>). The LIFA supports sampling rates of 200 Hz for wired communication and for 25 Hz wireless communication with either Bluetooth or Xbee/ZigBee.

A simplified Matlab implementation was done using the Matlab ArduinoIO Package (Giampiero Campa, MathWorks, Inc., <http://www.mathworks.com/matlabcentral/fileexchange/32374-matlab-support-package-for-arduino-aka-arduinoio-package>). We chose to use the sketch file adiosrv.pde from the provided files, the sketch file functioned in practice as an analog/digital input and output server for Matlab. The provided Matlab class `arduino.m` was installed for Matlab allowing the access to the input and output pins of Arduino. In other words, the sketch file was uploaded to Arduino Uno using the default IDE allowing us to write and read digital and analog values from the Arduino under Matlab. For full details on the ArduinoIO package, one is referred to documentation of the Arduino IO Package, and <http://code.google.com/p/arduino-v-neusci/> for the examples developed by us. Alternatively, the Arduino calls could have been implemented directly using the lower level serial port communication capability of Matlab. The Matlab implementation is useful for example with the widely used psychophysics package Psychophysics Toolbox for Matlab (Brainard, 1997).

## 2.2. Light control experiments

The use of the Arduino in neuroscience applications is demonstrated using three typical applications implemented in our laboratories, allowing also the demonstration of different technical characteristics of the Arduino LED stimulator system.

### 2.2.1. Mouse pupillometry

Technically the simplest demonstration application presented by us, is the light stimuli delivery from LEDs equipped with interference filters (Fig. 2) to measure the murine pupillary light reflex (Mure et al., 2007; Hussain et al., 2009). Recently similar LED-based chromatic pupillometry was employed by Herbst et al. (2011) to study the human pupillary light reflex (PLR). The mechanical shutter used previously by Mure et al. (2007) could be replaced either with an external transistor–transistor logic (TTL) 5 V trigger signal to Arduino's digital input, or with an integrated timing function directly for the used Python code (Arduino sketch `GuiArduinoLED.ino` and `GuiArduinoLED.py` the demonstration Python GUI front-end in <http://code.google.com/p/arduino-v-neusci/>). The corresponding Matlab implementation is `GuiArduinoLED.m`, and

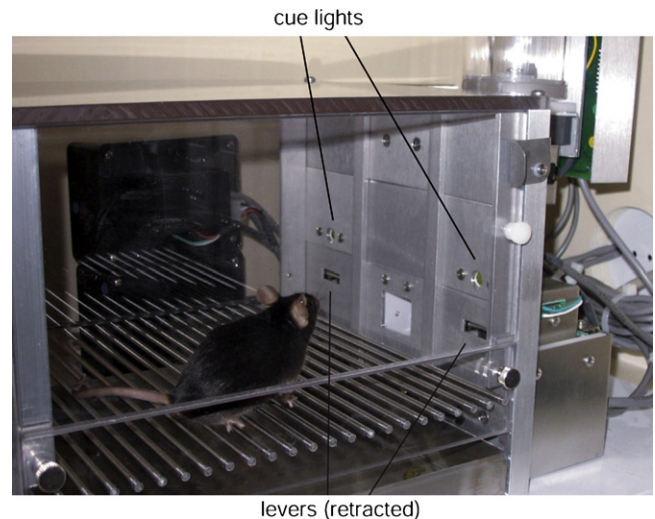


**Fig. 2.** Photo of LED light source (via fiber optics on the left) and pupillometer (Arrington ViewPoint, right below) equipped with additional infrared LEDs (above right) for measuring consensual rodent PLR.

the LabVIEW virtual instrument *GuiArduinoLED.vi*. The board schematics corresponding to the example code is shown in Fig. 3.

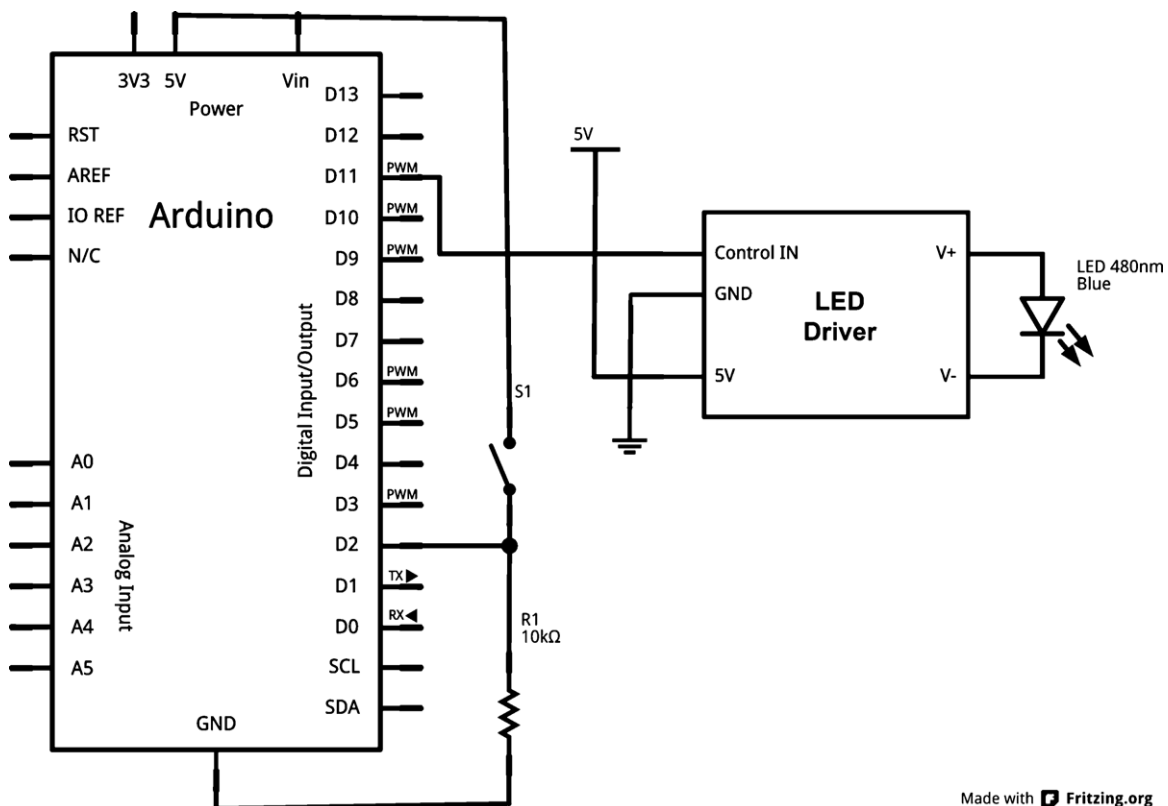
### 2.2.2. Cue light conditioning in rodents

In addition to driving LED intensity with the Arduino, it can be used to relay trigger signals from external sources or to generate the trigger directly from the code. One example of this kind of use, is to turn on and off a cue light based on the behavior of the mouse in the experimental paradigm of Malkki et al. (2010). The mouse in the “operant nose poke task” has to collect a sucrose pellet while



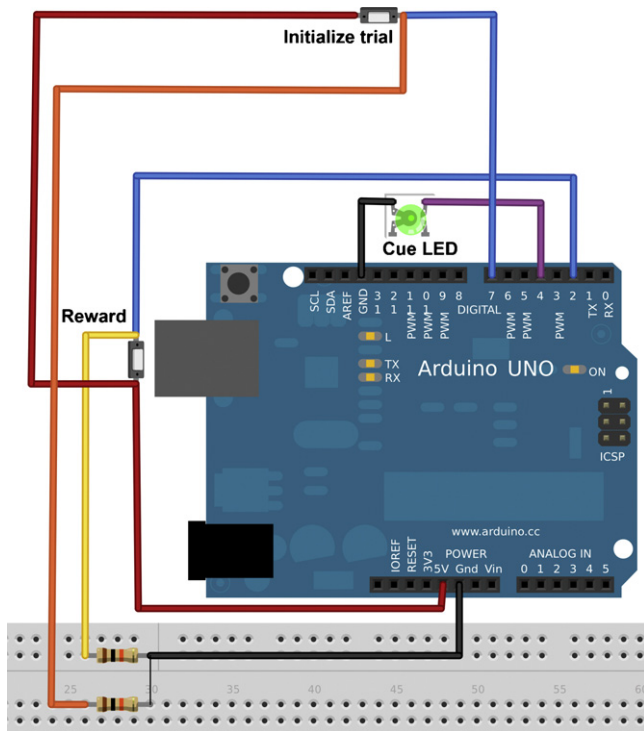
**Fig. 4.** Behavioral testing chamber for mice from Malkki et al. (2010). The behavioral box with green LED stimulus lights, two operant levers (shown in the withdrawn state) and food magazine (in the middle) on the front panel. *Operant nose poke task*: (1) cue light on → 30 s time window during which the animal can collect a sucrose pellet by poking in the reward tray → cue light goes after collection of reward or the 30 s timeout → 5–25 s pseudorandom inter-trial interval during.

the cue LED light is on by poking in the reward tray (Fig. 4), the cue light turning off upon successful collection or after a 30 s timeout. In contrast to the mouse PLR setup above, in this application Arduino can be run autonomously without any need of a control computer. Simplified breadboard schematics are shown in Fig. 5, and the electronics schematic shown in Fig. 6.



Made with Fritzing.org

**Fig. 3.** Schematics for Arduino UNO in rodent pupillometry. The digital input (D2) reads the signal initiating light stimulus corresponding to the use of mechanical Uniblitz shutter in previous setup (Mure et al., 2007). The switch is connected to the ground (GND) via a pull-down 10 kΩ resistor. The LED intensity is adjusted via a LED driver by the PWM output (PWM4 from digital pin 11) of Arduino Uno. Arduino schematic was developed using the Fritzing (<http://fritzing.org/>) software.



**Fig. 5.** Breadboard schematics for Arduino Uno in cue light task. Only a few connections are needed for the cue light control, digital input (pin 4) outputs 5 V (maximum current 50 mA) for the green LED when the 30 s trial is initiated with a 5 V signal to the digital input (pin 7). If the mouse collects the reward within the 30 s time-out period the “reward switch” signals the collection to digital input at pin 2 which turns off the green cue LED. The input switches are connected to the ground (GND) via pull-down 10 k $\Omega$  resistor. Arduino schematic was developed using the Fritzing (<http://fritzing.org/>) software.

### 2.2.3. Heterochromatic flicker photometry

The third application demonstrated for the Arduino setup was our heterochromatic flicker photometric (HFP) setup used for measuring ocular media density in humans (Teikari et al., unpublished results). The physical setup is illustrated in Fig. 7, and the technical specifications described in Teikari et al. (unpublished results). In heterochromatic flicker photometry (Bone and Landrum, 2004), two spectrally different LED channels need to be flickered in counterphase, while the human volunteer adjusts one of the intensity of the other flickering light until the flicker is minimized or eliminated.

**LED driving.** Two power LEDs with peak wavelengths at 405 nm (LedEngin, Inc., UV LED, LZ1-10UA00, 700 mA) and at 530 nm (Philips Lumileds™ Luxeon III LED, LXHL-LM3C, 1000 mA) were connected to constant current LED drivers (XP Power™ LDU0830S350, 350 mA) and intensity was modulated using pulse width modulation (PWM) signal controlled by Arduino Uno. The power LEDs were attached to heat sinks (Aavid Thermalloy, part no. 601403b06000,  $R_{hs} = 1.39^\circ\text{C/W}$ ) with a thermal adhesive (Aavid Thermalloy, Ther-O-Bond 1500) to ensure sufficient heat dissipation from the LEDs (Tao and Hui, 2012), and avoid reduction in light output and shift in the peak emission with heating of the LEDs even with the heatsinks (Watanabe et al., 1992; Poussset et al., 2010).

**User interface.** Light intensity was directly controlled by the subject, using a standard one-axis joystick (“User Joystick UP” and “User Joystick Down” in Fig. 8) and a confirm button for the fusion match (“User Button” in Fig. 8) connected to the three digital input pins of Arduino Uno with pull-down resistors (10 k $\Omega$  is a typically used value). The logical HIGH level of the joystick and button presses were provided by the 5 V voltage pin of the Arduino Uno. Alternatively one could have used the commercial

joystick/input Shield shields (e.g. DFRobot RB-Dfr-08 and Sparkfun Joystick Shield) for Arduino.

**Software.** The software front-end was developed by the authors using Python (*heterochromaticFlicker.py*) for the flicker demonstration (available from <http://code.google.com/p/arduino-v-neusci/>), and the corresponding Arduino sketch for the heterochromatic flicker fusion task being *heterochromaticFlicker.ino*. Alternative implementation was also provided for LabVIEW (file *heterochromaticFlicker.vi*).

## 3. Results

The quality of the output PWM signal was measured using a data acquisition card (DAQ, National Instruments™ USB-6210) with its supplied NI LabVIEW SignalExpress software for interactive data logging. The measurement results are shown in Fig. 9 with various different duty cycles.

In the cue light task (Section 2.2.2), the cue light (digital output) was triggered with a digital input signal, thus in some applications the latency from trigger to the output is of an interest. The measurement was done as above for the quality of the PWM signal. The measurement with a sampling rate of 2.5 kHz at a baud rate of 57,600 bps yields a latency of  $\approx 2.5$  ms, and at a baud rate of 115,200 bps yields a latency of  $\approx 1.2$  ms. Furthermore, if needed, the digital input–output behavior could be optimized for Arduino for example using external libraries such as the *digitalwritefast* (<http://code.google.com/p/digitalwritefast/>).

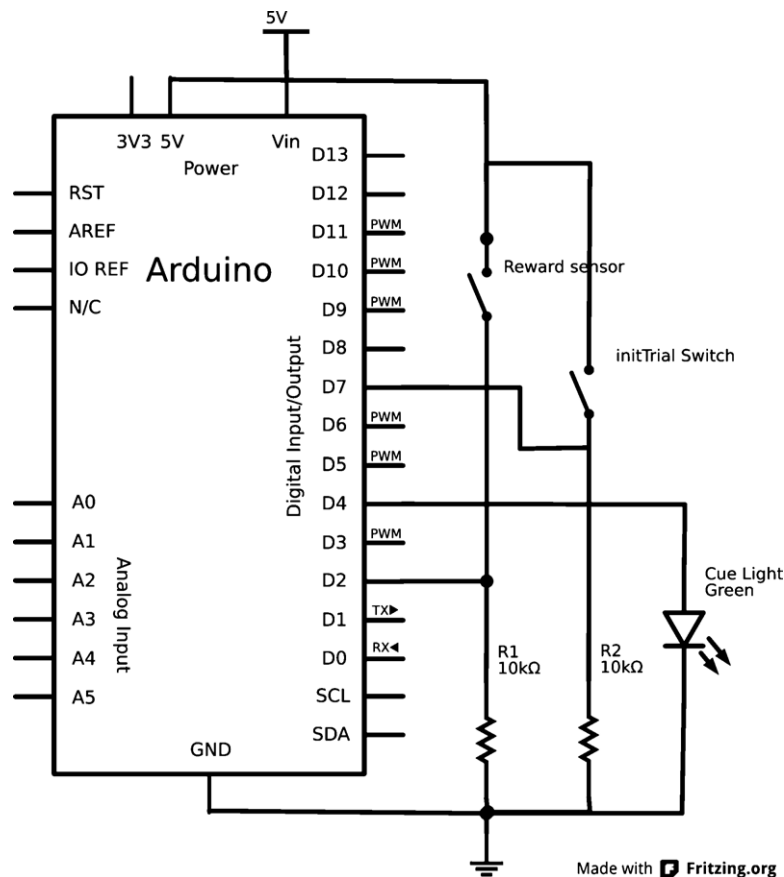
The linearity of the light output (irradiance) as a function of the duty cycle of output PWM signal was measured using a radiometer (International Light™ IL1700). The results of the measurements are shown in Fig. 10 for Luxeon K2 Cool White (light output of 120 lm at 1000 mA, LXK2-PW14-V00), using the default 8-bit PWM output of Arduino to drive XP Power™ 1000 mA constant current supply (LDU2430S1000), and with the *Timer1* library (<http://arduino.cc/playground/Code/Timer1>) for Arduino allowing 10-bit PWM resolution the Luxeon K2 LED being directly connected to the digital output pin of Arduino (50 mA maximum output current). The Python code (*bit10PWM.py*) and the corresponding Arduino sketch (*bit10PWM.ino*) for 10-bit PWM implementation are available for download from: <http://code.google.com/p/arduino-v-neusci/>. 3 Additionally, the *Timer1* library could be used if the PWM frequency, or the flicker frequency of the modulating envelope would like to be modified, the latter needed in systems to measure critical flicker fusion (CFF) frequency as done for example in Gregori et al. (2011) and in Teikari et al. (unpublished results). The reason for direct connection to the output pin was that we did not have LED driver sensitive enough for low duty cycles.

## 4. Discussion

The inexpensive Arduino-based LED stimulator system developed using off-the-shelf components described here was shown to behave according to design criteria. The pulse-width modulation (PWM) signal provided by the Arduino was shown to be of a good quality, thus leading the irradiance output of LEDs to be linear as a function of the duty cycle of PWM signal. The latency from digital input to digital output was shown to be sufficiently short for our applications, further supported by the more detailed timing precision analysis done by D’Ausilio (2011) for Arduino in behavioral neuroscience application.

Our approach was designed to be easily set up even without advanced skills in electronics in contrast to the project described by da Silva Pinto et al. (2011) that required the end-user to have the access on equipment making printed board circuits (PCBs). The





**Fig. 6.** Schematics for Arduino UNO in cue light task. In this case the Arduino can be run autonomously without the use of a control computer. All the functionality of the setup is programmed to the Arduino sketch (*lightCueTask.pde*), the provided Python file serving only demonstration purposes (*lightCueTask\_demo.py*). Arduino schematic was developed using the Fritzing (<http://fritzing.org/>) software.

use of USB-powered and interfaced ensured good compatibility with future computers compared to the solution of Rogers et al. (2012) interfacing the LEDs via parallel port that is becoming obsolete in modern desktop computers and laptops. Furthermore, the approach is highly modular so that the Arduino outputs PWM signal that can be used to drive the majority of LED drivers allowing

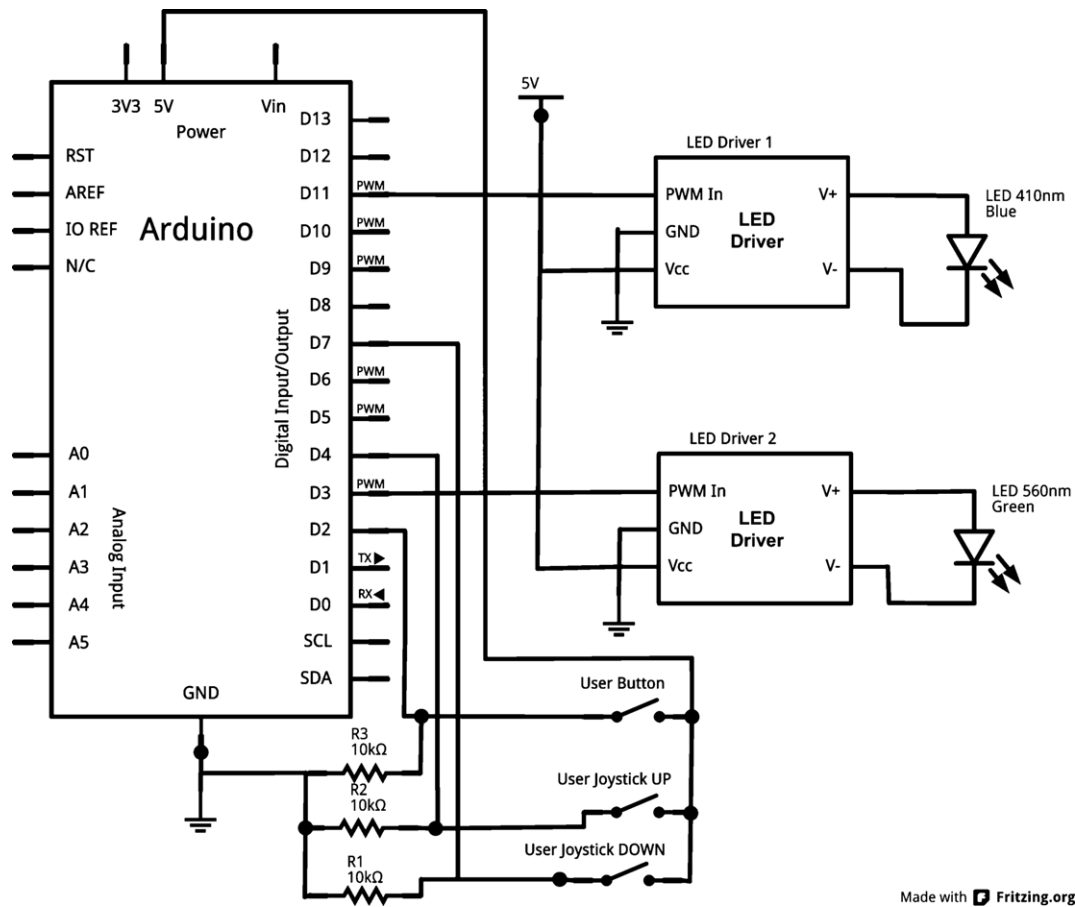
the end-users to select their components easily from commercial solutions based on their individual needs. Additionally, the Arduino can be controlled using various programming environments and it is not limited to some proprietary environments such as LabVIEW.

By choosing open-source solutions both in respect to hardware (Arduino) and programming environment (Python), the capabilities to modify the proposed LED stimulator are greatly broadened and allowing novel ways of interaction between the developers and end/users (De Paoli and Storni, 2011; Mellis and Buechley, 2012). Active user communities exist both around Arduino (e.g. Arduino Playground, <http://arduino.cc/playground/>) and Python (e.g. <http://www.python-forum.org/>). Python has gained popularity recently in general-purpose programming as well as in scientific computing (e.g. Langtangen, 2009). Python-based open-source scientific software has been developed for example for visual psychophysics [PsychoPy, Peirce, 2007], stimulus presentation in vision research [Vision Egg, Straw, 2008], and in brain–computer interfacing (BCI) systems [Pyff, Venthur et al., 2010]. Additionally, various solutions exist for integrating existing program code developed for example in C/C++ (<http://cython.org/>), Java (<http://jython.org/>), and Matlab [OMPC, Jurica and van Leeuwen, 2009] to Python program code.

The major limitation of the Arduino-based LED stimulator described herein is the narrow dynamic range of the light output that is only 8 bits ( $\approx 2.4$  log units) or 10 bits ( $\approx 3.0$  log units) optimizing timer-function of Arduino. This is over a magnitude lower compared to the previous report of 4.5 log unit dynamic range (Demontis et al., 2005), although the dynamic range obtained by us is sufficient for various applications. Given the modular structure of the designed system, the Arduino could be replaced with an



**Fig. 7.** The heterochromatic flicker photometric setup for measuring human ocular media density psychophysically. The IL1700 radiometer is used to calibrate the light intensity linearity of the LED light source (placed on top of the setup for the calibration) with a LED driver situated inside of the wooden box. The PWM signal is transmitted from a separate room for experimenter containing the Arduino Uno connected to the control computer.

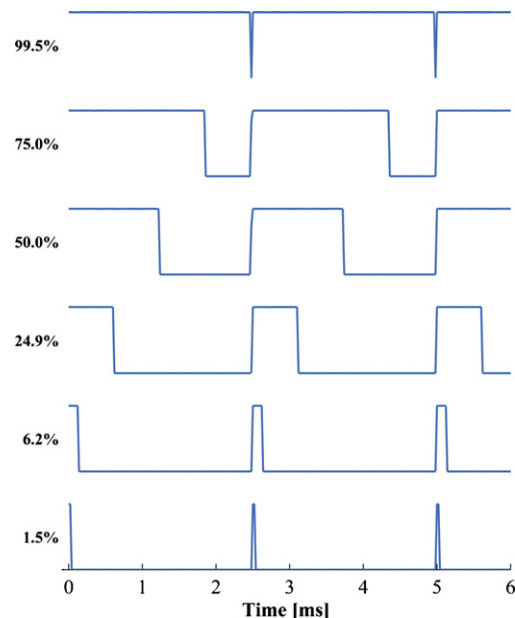


Made with Fritzing.org

**Fig. 8.** Schematics for Arduino UNO in heterochromatic flicker technique used in the ocular media density measurement by the authors (Teikari et al., unpublished results). Arduino schematic was developed using the Fritzing (<http://fritzing.org/>) software.

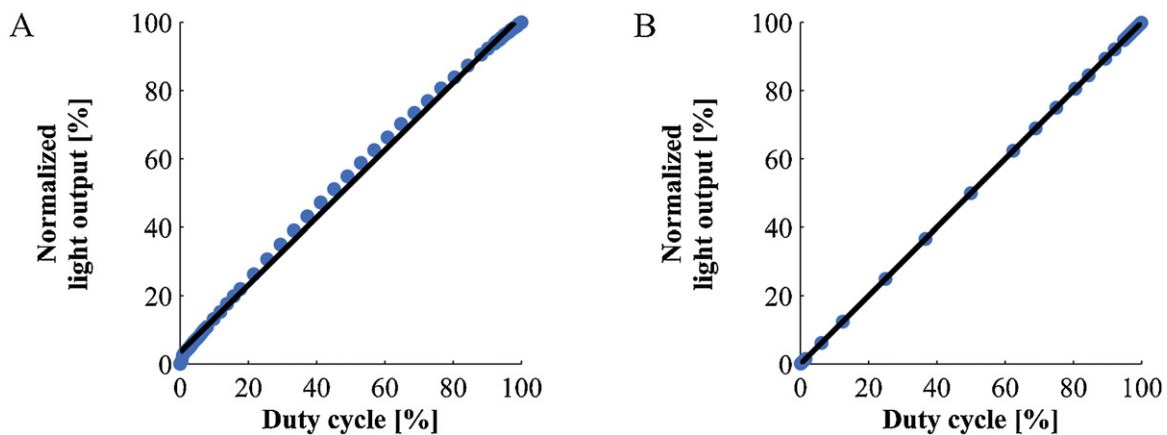
Arduino-compatible Maple Rev. 5 (Leaf Labs, <http://leafflabs.com/>) that is based on ARM (Advanced RISC Machine) processor family providing a 16-bit PWM output (dynamic range of  $\approx 4.8$  log units). Given that the hardware design of Arduino is open-source, advanced users can modify the existing solutions and design Arduino-compatible (for the current list of compatible boards see <http://arduino.cc/playground/Main/SimilarBoards>) boards for example with improved timer functions allowing higher dynamic ranges for light output.

In some applications requiring the measurement environment to be as free from artifacts as possible, as the case in precision metrology and in electrophysiology, the possible electromagnetic interference (EMI) caused by rapid switching (i.e. the pulse width modulation) of the LED current can cause artifacts. The mechanism of the EMI creating in PWM-driven LED systems is similar as for PWM-driven electrical motors as analyzed by Zhong et al. (1996). The magnitude of EMI emission depend on the LED current, current fall and rise times, cable shielding, grounding, and geometry of electrical conductors in the research setup (Ott, 2009). For proper measurement of EMI-induced artifacts on electrophysiological settings, one needs to do the measurements *in situ* with the actual cable geometry. For comparison, in the system of da Silva Pinto et al. (2011), the EMI emitted by the system was low enough for the system to be used in EEG recordings, thus we assumed that in our applications the EMI emitted would not pose a problem. Additionally, the used commercial components Arduino Uno and XP LED Driver were Federal Communications Commission (FCC) certified for low EMI emissions.



**Fig. 9.** The measured 10-bit PWM signals from Arduino Uno at different duty cycles (indicated on the left of the traces) using the `Timer1` library. The PWM frequency was the default 400 Hz (period of one cycle 2.5 ms). The sampling rate for acquisition was 50 kHz.





**Fig. 10.** Measured relation between the PWM duty cycle and the measured normalized light output (IL1700) for Arduino UNO. The used LED was Luxeon K2 Cool White (light output of 120 lm at 1000 mA, LXK2-PW14-V00). (A) The measurement with 8-bit PWM output with XP Power LED driver (LDU2430S1000),  $R^2 = 0.998$ . (B) With 10-bit PWM output using the Timer1 library connecting the LED directly to the PWM output pin of Arduino Uno,  $R^2 = 1.000$ . The blue points are the measured values, and black line the linear regression fit. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

In order to reduce the EMI emission one can either improve the design of the switching LED driving circuit (e.g. Wang and Xu, 2012), or use a LED driving circuit that doesn't output pulsed current. A recent commercial solution is the provided by IST (Integrated System Technologies Limited, Aldridge, UK) with its iDrive Quad LED driver that according to the specifications provides DC current output without switching with a 16-bit dynamic range. The IST iDrive Quad, however, is not directly compatible with our PWM-based solution as it can be only driven with constant voltage (1–10 V) or network lighting control protocols Digital Addressable Lighting Interface (DALI, <http://www.dali-ag.org/>) and DMX512/RDM (e.g. <http://www.opendmx.net/>) mainly used in architectural lighting control. Additionally, the dynamic range of the system could be increased by adding a switching transistor like insulated gate bipolar transistor (IGBT) to the output of the iDrive Quad or similar constant current supply, and switch the output current driving the transistor with the PWM output of Arduino.

When comparing the Arduino to existing data acquisition device (DAQ) solutions, the Arduino cannot provide the same level of temporal precision as dedicated precision DAQs. However, for most of the visual neuroscience solutions the DAQ approaches are often overqualified and overpriced as pointed out by Puts et al. (2005). The Arduino as a DAQ device was tested at site "Measuring Stuff: The Arduino DAQ Chronicles" (<https://sites.google.com/site/measuringstuff/the-arduino>), giving estimates for analog input sampling rate via serial connection to the hard drive at baud rate of 9600 bps to be approximately 26 samples per second, and at baud rate of 115,200 bps to be approximately 517 samples per second. The obtained analog input sampling rate is sufficient to replace oscilloscopes and logic analyzers in some applications as done demonstrated in the Arduinoscope project (<http://code.google.com/p/arduinoscope/>).

The sample rate can be further increased for burst writing the data only to the on-board SRAM of the Arduino (2 KB in Arduino Uno, and 8 KB in Arduino Mega) reaching sample rates of 8300 samples per second. The latter option of by-passing serial communication can be useful for on-board calculation based on analog input signal not requiring data logging. Additionally, the analog input could be used for example to correct the light output depending on the measured photoreceptor membrane voltage (Djupsund et al., 1995), LED junction temperature measured with various means (Siegal, 2006; Qu et al., 2010), or light output measured with a photodiode (Watanabe et al., 1992).

The computational performance of the Arduino platform in practice depends on the development of Atmel® (<http://www.atmel.com/>) microcontrollers.

For embedded applications where the Atmel-based performance is insufficient, an alternative would be to use either ARM-based Arduino-compatible boards such as Maple Rev. 5 (Leaf Labs, <http://leaflabs.com/>), or recent ARM-based board computers such as BeagleBoard (<http://beagleboard.org/>) and Raspberry Pi (<http://www.raspberrypi.org/>). The ARM-based board computers in practice are capable of doing many of the same things as Arduino while not being designed for the same target audience. ARM-based board computers provide more computing power and Linux as an embedded operating system directly on the board at a low price, Raspberry Pi having a retail price of \$25 (~20€). BeagleBoard and Raspberry Pi have less input/output pins compared to Arduino boards, thus the ARM-based board computers can be complemented with Arduino boards. BeagleBoard for example has an extension written to exploit Arduino sketches (<https://github.com/prpplague/Arduino-for-Userspace-Linux>). Similarly project for Raspberry Pi have been developed allowing Arduino sketches to be run on Raspberry Pi (<https://projects.drogon.net/raspberry-pi/wiringpi/>) extending the usability of the existing Arduino code.

In conclusion, the LED visual stimulator based on the Arduino microcontroller prototyping platform was found to be suitable for controlling LEDs in several neuroscience applications. The low-cost and ease of use of the system and ease of use makes it an attractive alternative to DAQ-based systems. The system can be used for a wide range of applications in educational and research environments with limited budgets or technical skills, and in particular for researchers, students and universities with limited resources.

## Conflict of interest

PT has a received a free sample XBee shield from Farnell.

## Acknowledgements

Financial support: ANR-09-MNPS-040, Retina France, Unadev, Rhône-Alpes Cible, Rhône-Alpes Cluster HVN, Federation des Aveugles et Handicapés Visuels de France, Ministère de l'Enseignement Supérieur et de la Recherche Français. We would like to thank Tuomas Poikonen for helpful comments on the manuscript, and David Weber for the help on mouse pupillometry.

## References

- Albeanu DF, Soucy E, Sato TF, Meister M, Murthy VN. LED arrays as cost effective and efficient light sources for widefield microscopy. *PLoS ONE* 2008;3(5):e2146.
- Bone RA, Landrum JT. Heterochromatic flicker photometry. *Arch Biochem Biophys* 2004;430(2):137–42.
- Brainard DH. The psychophysics toolbox. *Spatial Vision* 1997;10(4):433–6.
- Brophy JJ. Fluctuations in luminescent junctions. *J Appl Phys* 1967;38(6):2465–9.
- Buechley L, Eisenberg M. The LilyPad Arduino: toward wearable engineering for everyone. *IEEE Pervasive Comput* 2008;7(2):12–5.
- da Silva Pinto MA, de Souza JKS, Baron J, Tierra-Criollo CJ. A low-cost: portable, micro-controlled device for multi-channel LED visual stimulation. *J Neurosci Methods* 2011;197(1):82–91.
- De Paoli S, Storni C. Prodisage in hybrid networks: sociotechnical skills in the case of Arduino. *New Review of Hypermedia and Multimedia* 2011;17(1):31–52.
- Demontis GC, Sbrana A, Gargini C, Cervetto L. A simple and inexpensive light source for research in visual neuroscience. *J Neurosci Methods* 2005;146(1):13–21.
- Djupsund K, Kouvalainen E, Järvillehto M. A digital feedback controller application for studying photoreceptor adaptation by 'voltage clamp by light'. *J Neurosci Methods* 1995;62(1–2):29–36.
- D'Ausilio A. Arduino: a low-cost multipurpose lab equipment. *Behav Res Methods* 2011;44(2):305–13.
- Fadda A, Falsini B. Precision LED-based stimulator for focal electroretinography. *Med Biol Eng Comput* 1997;35(4):441–4.
- Faludi R. Building wireless sensor networks: with ZigBee, XBee, Arduino, and Processing. Sebastopol: O'Reilly Media, Inc; 2010.
- Grasel J, Vonnegut W, Dodds Z. Bitwise biology: crossdisciplinary physical computing atop the Arduino. In: 2010 AAAI spring symposium series; 2010.
- Gregori B, Papazachariadis O, Farruggia A, Accornero N. A differential color flicker test for detecting acquired color vision impairment in multiple sclerosis and diabetic retinopathy. *J Neurol Sci* 2011;300(1–2):130–4.
- Herbst K, Sander B, Milea D, Lund-Andersen H, Kawasaki A. Test–retest repeatability of the pupil light response to blue and red light stimuli in normal human eyes using a novel pupillometer. *Front Neurol* 2011;2:10.
- Hogg C. Stimulus devices, calibration, and measurement of light. In: Heckenlively JR, Arden GB, editors. *Principles and practice of clinical electrophysiology of vision*. 2nd ed. Cambridge: The MIT Press; 2006.
- Holman B. LED light source: major advance in fluorescent microscopy. *Biomed Instrum Technol* 2007;41:461–4.
- Hussain RZ, Hopkins SC, Frohman EM, Eagar TN, Cravens PC, Greenberg BM, et al. Direct and consensual murine pupillary reflex metrics: establishing normative values. *Auton Neurosci* 2009;151(2):164–7.
- Isoyama N, Terada T, Akita J, Tsukamoto M. A method to control LED blinking for position detection of devices on conductive clothes. In: *Proceedings of the 9th international conference on advances in mobile computing and multimedia*. MoMM; 2011. p. 123–30.
- Jones R, Haufe P, Sells E, Iravani P, Olliver V, Palmer C, et al. RepRap – the replicating rapid prototyper. *Robotica* 2011;29(1):177–91.
- Jurica P, van Leeuwen C. OMPIC: an Open-Source MATLAB®-to-Python compiler. *Front Neuroinform* 2009;3:5.
- Kato Y. Splish: a visual programming environment for Arduino to accelerate physical computing experiences. In: *Creating connecting and collaborating through computing (C5)*, 2010 eighth international conference; 2010. p. 3–10.
- Langtangen HP. A primer on scientific programming with Python. New York/Heidelberg: Springer; 2009.
- Malkki HAI, Donga LAB, de Groot SE, Battaglia FP, Pennartz CMA. Appetitive operant conditioning in mice: heritability and dissociability of training stages. *Front Behav Neurosci* 2010;4:171.
- Margolis M. Arduino cookbook. 1st ed. Sebastopol: O'Reilly Media; 2011.
- Mellis D, Buechley L. Collaboration in open-source hardware: third-party variations on the Arduino Duemilanove. In: *Proceedings of the ACM 2012 conference on computer supported cooperative work*; 2012. p. p1175–1178.
- Mure LS, Rieux C, Hattar S, Cooper HM. Melanopsin-dependent nonvisual responses: evidence for photopigment bistability in vivo. *J Biol Rhythms* 2007;22(5):411–24.
- Narra P, Zinger DS. An effective LED dimming approach. In: *IEEE industry applications conference*, 2004, 39th IAS annual meeting, vol. 3. IEEE; 2004. p. 1671–6.
- Nishigaki T, Wood CD, Shiba K, Baba SA, Darszon A. Stroboscopic illumination using light-emitting diodes reduces phototoxicity in fluorescence cell imaging. *BioTechniques* 2006;41(2):191–7.
- Nishimura M, Shirasawa H, Song W. A light-emitting diode light source for imaging of neural activities with voltage-sensitive dyes. *Neurosci Res* 2006;54(3):230–4.
- Nygaard RW, Frumkes TE. LEDs: convenient: inexpensive sources for visual experimentation. *Vision Res* 1982;22(4):435–40.
- Ott HW. *Electromagnetic compatibility engineering*. 1st ed. Hoboken: John Wiley & Sons; 2009.
- Parkova I, Valishevskis A, Ziemele I, Vilumsone A. Integration of optical fibres into textile products. *Adv Mater Res* 2011;222:162–5.
- Peirce JW. PsychoPy–Psychophysics software in python. *J Neurosci Methods* 2007;162(1–2):8–13.
- Pokorny J, Smithson HE, Quinlan J. Photostimulator allowing independent control of rods and the three cone types. *Vis Neurosci* 2004;21(03):263–7.
- Pousset N, Rougié B, Razet A. Impact of current supply on LED colour. *Light Res Tech* 2010;42(4):371–83.
- Puts MJ, Pokorny J, Quinlan J, Glennie L. Audiophile hardware in vision science; the soundcard as a digital to analog converter. *J Neurosci Methods* 2005;142(1):77–81.
- Qu X, Wong S, Tse CK. Temperature measurement technique for stabilizing the light output of RGB LED lamps. *IEEE Trans Instrum Meas* 2010;59(3):661–70.
- Rogers B, Shih YI, Garza BDL, Harrison JM, Roby J, Duong TQ. A low cost color visual stimulator for fMRI. *J Neurosci Methods* 2012;204(2):379–82.
- Rumyantsev SL, Shur MS, Bilenko Y, Kosterin PV, Salzberg BM. Low frequency noise and long-term stability of noncoherent light sources. *J Appl Phys* 2004;96(2):966–9.
- Salzberg B, Kosterin P, Muschol M, Obaid A, Rumyantsev S, Bilenko Y, et al. An ultra-stable non-coherent light source for optical measurements in neuroscience and cell physiology. *J Neurosci Methods* 2005;141(1):165–9.
- Scholfield C, Murdock M. Pulse-modulated light source for psychometric and vision experiments. *J Neurosci Methods* 1987;19(3):203–7.
- Schubert EF, Kim JK. Solid-state light sources getting smart. *Science* 2005;308(5726):1274–8.
- Siegal B. Practical considerations in high power LED junction temperature measurements. In: *International conference on electronics manufacturing and technology*, 2006, 31st international conference; 2006. p. 62–6.
- Spacek M, Blanche T, Swindale N. Python for large-scale electrophysiology. *Front Neuroinform* 2009;2:9.
- Stankus M, Penhaker M, Cerny M, Bamidis PD, Pallikarakis N. Low cost data acquisition system for biomedical usage. In: *XII Mediterranean conference on medical and biological engineering and computing*, vol. 29 of IFMBE proceedings. Berlin/Heidelberg: Springer; 2010. p. 883–5.
- Straw AD. Vision egg: an Open-Source library for realtime visual stimulus generation. *Front Neuroinform* 2008;2.
- Sun R, Bouchard MB, Hillman EMC. SPLASH: open source software for camera-based high-speed: multispectral in vivo optical image acquisition. *Biomed Opt Express* 2010;1(2):385–97.
- Svilainis L. LED PWM dimming linearity investigation. *Displays* 2009;29(3):243–9.
- Svilainis L. Comparison of the EMI performance of LED PWM dimming techniques for LED video display application. *J Disp Technol* 2012;8(3):162–5.
- Tao X, Hui SY. Dynamic photoelectrothermal theory for light-emitting diode systems. *IEEE Trans Ind Electron* 2012;59(4):1751–9.
- Teikari P, Najjar RP, Knoblauch K, Dumortier D, Cooper HMC, Gronfier CG. A refined flicker photometry technique to measure the ocular media density, unpublished results.
- van der Linden J, Schoonderwaldt E, Bird J, Johnson R. MusicJacket – Combining motion capture and vibrotactile feedback to teach violin bowing. *IEEE Transactions on Instrumentation and Measurement* 2011;60(1):104–13.
- Venthur B, Scholler S, Williamson J, Dähne S, Treder MS, Kramarek MT, et al. Pyff – a pythonic framework for feedback applications and stimulus presentation in neuroscience. *Front Neuroinform* 2010;4:100.
- Viswanathan S, Frishman LJ, Robson JG, Walters JW. The photopic negative response of the flash electroretinogram in primary open angle glaucoma. *Invest Ophthalmol Vis Sci* 2011;42(2):514–22.
- Wang J, Xu J. Peak current mode bifrequency control technique for switching DC–DC converters in DCM with fast transient response and low EMI. *IEEE Trans Power Electron* 2012;27(4):1876–84.
- Warren J, Adams J, Molle H. *Arduino robotics*. New York: Apress; 2011.
- Watanabe T, Mori N, Nakamura F. A new superbright LED stimulator: photodiode-feedback design for linearizing and stabilizing emitted light. *Vision Res* 1992;32(5):953–61.
- Wheat D. *Arduino internals*. New York: Apress; 2011.
- Wilson JD, Adams AJ, Murphy P, Eswaran H, Preissl H. Design of a light stimulator for fetal and neonatal magnetoencephalography. *Physiol Meas* 2009;30(1):N1–10.
- Zhong E, Lipo TA, Jaeschke JR, Gritter D. Analytical estimation and reduction of conducted EMI emissions in high power PWM inverter drives. In: *IEEE power electronics specialists conference*, 1996, 27th annual conference; 1996. p. 1169–75.