A flexible Teensy microcontroller based interface for wide-field optical imaging during behavioral experiments

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**Abstract**

Systems neuroscience experiments often require the integration of precisely timed data acquisition and behavioral control. While many commercial systems have been designed to meet various needs, they often fail to offer flexibility that allows for integration across diverse or new experimental designs. . For example, it has been difficult to integrate recently developed sCMOS cameras with various input and output devices, for high speed, large scale calcium imaging analysis of neuronal circuits during behavior. We here developed Teensy 3.2 microcontroller-based interface that offers high-speed, precisely timed digital data acquisition of behavioral data, and digital and analog outputs for controlling sCMOS camera and other devices. We demonstrate the efficacy and the temporal precision of the Teensy interface in two experimental settings. In one example, we demonstrate the use of Teensy interface for reliable recording of an animal’s directional movement on a spherical treadmill, along with simultaneous control of an imaging device for high speed image acquisition. In another example, we demonstrate the use of Teensy interface for temporally precise delivery of auditory and visual signals in a trace conditioning learning behavioral paradigm, while controlling a camera for image acquisition. These examples demonstrate that Teensy 3.2 equipped with its hardware modules, provides an efficient and flexible platform capable of integrating sCMOS camera into behavioral experimental designs, for high-speed and temporally precise imaging and behavior output for systems neuroscience experiments.

**Introduction**

Recent advance in sCMOS cameras and genetically encoded calcium sensors enable neuroscientists to perform fluorescence imaging of thousands of individual cells’ activity, allowing the analysis of networks related to behavior (Klaus, et al., 2017; Barbera, et al., 2016; Mohammed, et al., 2016; Markowitz, et al., 2018). However, the integration of high speed sCMOS cameras with devices needed to monitor and control behavioral progress has been difficult. In particular, the driver for sCMOS is difficult????

There are many strategies to control the temporal precision of an experiment, where neural activities can be precisely aligned with behavioral progress, such as various Analog/Digital interface that can be precisely controlled by Labview and Matlab. However, integration of sCMOS with these systems has been difficult due to driver issues?

Over the last several years, microcontrollers traditionally used by hobbyists have gained traction across a variety of scientific fields (Sanders & Kepecs, 2014; D'Ausilio, 2012; Chen & Li, 2017; Husain, Hadad, & Zainal Alam, 2016). Microcontrollers are small, open-source, and low-cost, allowing for easy customization and implementation. Arduino UNO is the first major mircrocontroller that gained popularity in the 1990s, which is capable of delivering precisely timed digital outputs with microsecond time resolution, while using user-friendly software functions. Recently, Teensy 3.2 started to gain increasing popularity, due to its additional feature of delivering analog output in addition to the features of the Arduino UNO. Teensy uses the software environment as Arduino, which is intuitive to learn without the need of advanced programming experience (D'Ausilio, 2012). Because these microcontrollers are low cost, they can be easily scaled for multiple experiments simultaneously. Since the software is open-source and the programming language is intuitive, microcontrollers can be easily adapted to various experimental needs including the integration of newly developed instrument (D'Ausilio, 2012).

Camera control via an Arduino device that initiates only the start of an imaging sequence has been previously shown (Micallef, Takahashi, Larkum, & Palmer, 2017). However, a limitation of this approach is that it is necessary to synchronize frame timing with behavioral data after the experiment is complete, which is inexact and may necessitate interpolation. However, Arduino and Teensy devices can instead be used to precisely time imaging capture for each frame. A common technique in laboratory studies using more expensive AD converters is to set up an imaging device to utilize an “external trigger”, where the rising phase of a digital pulse or TTL pulse either initiates a sequence of internally clocked image captures. One possibly concern with this approach is that imprecise triggering of each frame based on a different digital pulses could introduce jitter in digital pulse delivery causing frame loss and can also necessitate interpolation for many statistical analyses. In particular, behavioral data must be precisely aligned to imaging data in experiments that utilize imaging. Thus, there currently exists a need to engineer a device capable of delivering continuous, precisely timed digital pulses that can synchronize other experimental events with camera control.

Here, we demonstrate in two simple experimental paradigms that the Teensy 3.2 is indeed a simple, low-cost, flexible device capable of coordinating highly accurate data acquisition, and sound and stimulus delivery with image capture. In order to align experimental data with imaging data, frame capture should be instantiated on a frame-by-frame basis. The Teensy 3.2 is capable of keeping highly accurate and low-bias timing that allow it to reliably instantiate frame capture with highly regular intervals while delivering stimuli or recording experimental data with microsecond-level precision. This removes the need for post-hoc interpolation or time-alignment between different external devices.

**Methods**

*Motor acquisition experiment*

In this experiment, we performed motion tracking using two ADS-9800 gaming sensor ((<https://www.tindie.com/products/jkicklighter/adns-9800-laser-motion-sensor/>, vendor, part number), while delivering digital pulses to sCMOS camera to trigger image acquisition at 20Hz. The overall design for this experiment is shown in Figure 1A. Two ADNS-9800 gaming sensor boards were attached at the equator of a 3D-printed half-sphere in which a large, buoyant Styrofoam ball is floated by house air as described previously (REF--Dombeck, Khabbaz, Collman, Adelman, & Tank (2007)). These sensors lay at an angle of approximately 75 degrees from one another, so that the y-readings of both sensors can be used to compute linear velocity, and the x-readings can be used to compute rotational velocity.

(vendor, partnumber?) The output from Teensy was connected to the sCMOS camera with standard wire?. To acquire motor sensor data and to send digital pulses to sCMOS, we utilized the “IntervalTimer” function available in the standard Teensy library, which allows for calling different functions with microsecond precision. We used it to call a main function that sends out a digital pulse to sCMOS to capture a frame, collects data from the two ADNS-9800 sensors, and sends the motion data to a computer. The Teensy also has the very useful “ellapsedMicros” and “ellapsedMillis” libraries built in to the Teensyduino library, which act as time accumulators. Teensyduino can be downloaded separately for the Arduino, they come preinstalled in the Teensyduino library.

To extract readings from these sensors, we utilized functions that are freely available on Github (<https://github.com/markbucklin/NavigationSensor>), which are a modified version of the ADNS-9800 library (<https://github.com/mrjohnk/ADNS-9800>).

that are freely available on and abstract the complexity of acquiring motion data to a user-friendly level. In particular, this repository contains the ADNS9800 library, which is a modified version

Via the ADNS9800 library, we read from the “motion burst” register of each sensor. On every call to the main function, we acquired the accumulated displacement over the previous 50 milliseconds in both the x and y directions. For the counts per inch setting we used a value of 3400 counts per inch, the default setting. As previously mentioned, during this interrupt, a digital “on” pulse that lasts for approximately 1 ms is sent out of a digital pin using the DigitalIO library (<https://github.com/greiman/DigitalIO>). This library allows us to use the functions “fastPinMode” and “fastDigitalWrite’, for example, which reduce the latency introduced by turning pins on, off, or setting their “mode” (to INPUT or OUTPUT, for example). Instead of using the default Arduino programming environment to upload our code to the Teensy, we used PlatformIO (<https://platformio.org/>), an add-on to the widely-used Atom text editor (<https://atom.io/>). This allowed us to easily build and upload our multi-folder library to the Teensy.

To set the parameters in Teensy???, after the main script was uploaded to the Teensy, we wrote a simple MATLAB-based graphical user interface that can be used on a desktop or laptop connected via a USB to the Teensy. In principle, however, this graphical user interface could be written in Python or any other programming language. Using this interface, the user enters the length of the experiment and the frequency of data acquisition. This frequency will determine the frequency with which digital pulses are sent to notify an external device such as a CMOS camera to capture an image, for example, and also determine the frequency with which accumulated motor information will be recorded by the PC. The PC or laptop sends this information over a serial connection to the Teensy utilizing a bidirectional microUSB-USB cable.

In a proof-of-concept experiment (Figure 3), we recorded a 10 minute long session of a mouse running on the spherical treadmill, and data was acquired at 20 Hz, with concomitant digital outputs that could be used to trigger sCMOS camera for image capture or a different device.

The mouse’s speed was computed using the y-coordinates of each ADNS-9800 sensor, and the total distance travelled at any one time point was computed using the following equation:

Where yR and yL are the y readings from the left and right sensors, and is the angle between the two sensors (75 degrees). Velocity was computed as the distance divided by the time between two adjacent frames. Times and distances travelled were recorded by the Teensy 3.2, and the timings of digital pulses were measured by an external device at 3051.76 Hz (Tucker-Davis Technologies RZ5D (TDT RZ5D)).

After analyzing the time stamps acquired by the TDT RZ5D system, we noticed that there was a very small timing drift (approximately 30 microseconds per second). To confirm that the frequency of data acquisition and timing of the corresponding digital pulses didn’t affect this drift, we repeated 5 minute recording sessions without a live mouse at 20, 50, and 100 Hz. These recordings used an identical script, except we embedded a 500 microsecond delay between the start and end of the digital pulse (“delayMicroseconds(500)”) instead of a 1 millisecond delay (“delay(1)”).

*Classical conditioning experiment*

In this experiment, we utilized Teensy to deliver sound and puff to control the progress of a trace conditioning behavioral paradigm, while delivering digital pulses to sCMOS camera to trigger image acquisition at 20Hz. The general setup is shown in Figure 1B. In a trace conditioning experiment utilizing this setup, a head-fixed mouse would first be exposed to a 9500 Hz tone concomitantly with a light stimulus, and then receive a gentle eye puff after a brief memory trace interval.

To deliver an audible sound through Teensy, we used a “prop shield module available for Teensy (vendor, part number), which is” an easy-to-use add-on capable of amplifying analog output signals (shown in Figure 2B as pin A14). If stereo outputs are desired, the manufacturer also offers an audio shield (<https://www.pjrc.com/store/teensy3_audio.html>) that is capable of stereo output, as demonstrated previously (Solari, Sviatkó, Laszlovsky, Hegedüs, & Hangya, 2018).Prop shield was attached to Teensy with 14x1 double insulator pins (Catalog number?), with the output connected to a speaker, as demonstrated in Figure 2B. The prop shield can power speakers with resistances up to 8 ohms (https://www.pjrc.com/store/prop\_shield.html). We also directed digital outputs from the Teensy to activate a LED light concomitant with the sound, and a puff as an aversive stimulus following each sound/light combination. Meanwhile, digital pulses to control sCMOS camera were programmed to occur every 50ms.

We here utilized “elapsedMicros” in order to reliably time all of the experimental events. “elapsedMicros” objects serve as time incrementers, that increment time at the microsecond time scale beginning every time that its value is set to zero. Every 50 ms, this code called a main function that updated the status of the digital pins associated with the “puff” and the light, and updated the amplitude of the 9500 Hz sine wave (amplitudes were set to 0.05 during audio stimulus time periods, and 0 elsewhere). Also, at the termination of a trial, this function incremented the trial number. Finally, a 1 ms digital pulse was delivered via another pin to instantiate a theoretical camera trigger. The speaker, camera, puff, and light source can be attached to the microcontroller using simple coaxial cables with SMA connectors, as shown in Figure 1A. The same programming environment (PlatformIO on top of Atom) was utilized, and functions such as “fastPinMode” and “fastDigitalWrite” were utilized to decrease latency.

In order to begin experiments with the Teensy, we wrote in MATLAB a simple graphical user interface that can be used on a desktop or laptop. With this, a user enters the length of the each trial and the number of trials desired. The PC or laptop sends this information over a USB connection to the Teensy, which in turn reports information about the experiment, in particular the frames during which the tone is on, the puff is on, or the light is on, and the experimental and trial times (in milliseconds) at the beginning of each IntervalTimer function call.

In our proof-of-concept experiment (Figure 3), the puff, tone, and camera trigger pins were all attached to and were recorded by the same external device (TDT RZ5D) at 3051.76 Hz for the puff and camera trigger pins, and 24414.0625 Hz for the tone pin. The tone pin was measured directly (not through the amplifier). We performed a mock-recording consisting of 50 trials of 20 seconds length each, where sound and light output pins were programmed to turned on 11.1 seconds into each trial for 700 ms, and the pin used to generate the aversive puff stimulus was turned at 12.05 seconds into each trial for 100 ms.

In order to measure latency (Figure 4Bi and iii), we acquired the timing of the camera digital pulse, according to the TDT system, that corresponds to the exact frame during which the audio signal was turned on. We then acquired the timing of either the puff pin onset or the timing of the onset of the audio signal. In order to measure the onset of the audio signal, we took the raw recording and high-pass filtered the signal using a 6th-order Butterworth filter, a bandpass frequency of 1000 Hz, and a “zero-phase digital filter” (MATLAB command “filtfilt”). Then, we took the absolute value of the Hilbert transform of the filtered signal to acquire an amplitude envelope. After finding the amplitude envelope, we found those values that exceeded a value of 0.005. The first time point that the amplitude crossed this threshold was considered the tone onset, and the next time point that dropped below this threshold was considered the tone termination.

*Statistics*

Linear models were constructed using the “fitlm” function in MATLAB 2017b. Theoretical timings, to which measured timings were compared, were each taken to be timings beginning at 0 seconds in equal increments of 50 milliseconds for both experiments.

**Results**

**Add a paragraph about the need of a better and customizable interface to integrate sCMOS camera and behavior, without the need of traditional ephys instruments.**

Microcontrollers such as Arduino UNOs have gained popularity in neuroscience research due to their user-friendly interface and their flexibility of device integration (D'Ausilio, 2012; Chen & Li, 2017; Micallef, Takahashi, Larkum, & Palmer, 2017). However, Arduino UNO does not have direct analog output. Recently, has been developed, which The interval timer….Recently, Teensy has been developed, which has a direct analog output. In addition, Teensy has … … Further, while the Arduino UNO has several useful timing libraries, it lacks the IntervalTimer function, which in particular is optimal for precise control of experiments and precise acquisition of experimental data. This function takes as input a single main function and the time, in microseconds, desired between calls to this function. In addition, the Teensy 3.2 software has the built-in capability to utilize the elapsedMicros and elapsedMillis libraries. These libraries serve as highly accurate time accumulators that can be used to time experimental events to microsecond or millisecond accuracy, respectively. Arduinos can utilize these latter functions by downloading an additional library, though they come by default with the Teensy library. This is a desirable alternative to the IntervalTimer when the “interrupts” utilized by the IntervalTimer could interfere with other components of the code, such as audio output.

Here, we present Teensy based interface to integrate sCMOS camera image acquisition and behavioral experimental control.

To demonstrate the feasibility of Teensy based interface for precise data acquisition and control during behavioral experiments, we constructed a setup (Figure 1Ai and 1Aii), torecord animal locomotion data from two ADNS-9800 motion sensor boards reading the position of a spherical treadmill, while delivering digital outputs to drive a sCMOS camera. As shown in Table 1, the total cost is approximately $80.

To measure locomotion from awake head fixed mice, we used Teensy interface to record from two ADNS-9800 motion sensors. These sensors are affixed to a “spherical treadmill” setup, as described by Dombeck, Khabbaz, Collman, Adelman, & Tank (2007). Mice are surgically fitted with a head plate and imaging window, and headfixed above a house air floated ball (Figure 1Aii).

ADNS-9800 sensor boards are inexpensive, and are more sensitive than regular computer mice as used in previous designs and can measure 8200 counts per inch, providing a more accurate measure of locomotion parameters. Additionally, ADNS-9800 sensors have a high maximum sampling rate of 12000 frames per second (<https://datasheet.octopart.com/ADNS-9800-Avago-datasheet-10666463.pdf>). Further, accumulated displacements can be stored in the sensors between readings, because ADNS-9800 sensors store motion data in 16 bits instead of the more standard 8 bits.

ADNS-9800 sensors were commanded via….library. This library and these sensors highlight the benefits of working with low-cost and open source software: because of the ubiquity of Arduino microcontrollers, a large hobbyist community has developed and contributed software and devices that have the potential to be useful to the research community and accelerate the development of novel experimental design. For example, the low-cost ADNS-9800 sensor boards are fashioned by a very small company started by a hobbyist (https://www.tindie.com/stores/jkicklighter/). Useful add-ons and libraries are commonplace, and both contribute to the flexibility of these widely available microcontrollers.

With these sensors, we read displacements and converted them directly to micrometer displacements using the internal calibration of the sensors. Proper wiring is also simple and is demonstrated in Figure 2B. The connections demonstrated using dotted lines can be replaced with jumper wires or sturdier, longer lasting wire. No external capacitors or resistors are needed.

To test the fidelity and temporal accuracy while maintaining alignment with imaging data, we recorded the…., while mice are running on the spherical ball. We calculated the velocity of the mouse, with an average of… standard deviation of …which is in agreement with the general observation as with previous studies (see, for example, (Dombeck, Khabbaz, Collman, Adelman, & Tank, 2007)). When we measured the digital output timing with an oscilloscope?, we found that digital outputs are precise, with a perfect linear relationship, and a 28.9us per 50ms delay, thus the actual frequency was 49.99? Hz instead of 50 Hz..

To further verify the accuracy of the intervalTimer, we repeated recordings at 2Hz, 20hz and 100Hz, and found that the actual frequency waw 2.00001?Hz and 19.9995? Hz respectively. This accuracy is consistent with that previously reported using an Arduino UNO where Arduino executed 1.001Hz, when 1hz was set in the intervaltimer. (D'Ausilio, 2012). Together, these results demonstrate the temoporal precision of the Teensy commended with the IntervalTimer function. In addition, it underscores the utility of the Teensy in triggering frame-capture during long recording experiments for precise alignment of neuronal data with behavioral states (Micallef, Takahashi, Larkum, & Palmer, 2017).

*Trace conditioning*

In the second experiment (Figure 1B and 2B), we constructed a Teensy based setup for trace conditioning learning experiment, where a mouse is trained to associate conditioned stimuli (tone and/or light) with a subsequent unconditioned stimulus (an eye puff) separated by a brief time window.We set up the Teensy to deliver conditioned stimuli and to record the timing of ??. To deliver an auditory stimuli, we used a plug and play hardware amplifier (prop shield) to amplify the analog output from the Teensy, which can then drive speakers of both 4 and 8 ohms. Three sets of 14x1 double insulated pins for connecting the Teensy to the prop shield. In total, this setup costs approximately $40, excluding general equipment.

We recorded the timings of each digital outputs and compared them to the theoretical timings with samples spaced at exactly 50ms apart, as shown in Figure 4A. Similar to the observation in the locomotion experimental design, the measured timings were close to the theoretical timings, with a 30 microseconds delay per sample. Additionally, audio and puff signals showed no timing drift, mean, standard deviation?

We further quantified sound onset latency, sound duration, puff latency, and puff duration. As shown in figure 4Biii, the digital output for eye puff showed no delay from the theoretical time (0 seconds, with a standard deviation??). The duration of the puff digital pulse was both highly accurate and consistent, and was only 20us shorter over the 50 trials. Sound latency, while non-negligible, was both precise and predictable: it averaged 7.6 + 0.9 milliseconds. Because of the consistency of the timing latency, it would be easy to adjust for this latency within the code, in this case by instantiating a change in signal amplitude 7.6 milliseconds earlier than the corresponding frame capture. The value that we observed was similar to the value of 6.9 + 0.9 milliseconds that was observed in a similar design utilizing a Teensy 3.2, where the Teensy was used to play a pre-recorded sound after stimulation by a Bpod behavioral control system (Solari, Sviatkó, Laszlovsky, Hegedüs, & Hangya, 2018).

To further demonstrate the feasibility of modulating sound intensity while maintaining frequency accuracy, we delivered sound of……Using our design, wherein we modulated the amplitude of a sine wave in order to deliver a sound, we had very precise results, with a range of timings right around 700 ms with a range of 2.9 ms. Other implementations of the Audio library could potentially offer even more precision, if so desired. For example, if one needed to utilize a precise sound sequence in an experiment, they could upload the sound sequence as a .wav file and utilize the Teensy to play the pre-recorded sound (Solari, Sviatkó, Laszlovsky, Hegedüs, & Hangya, 2018). However, our design can be implemented very simply, utilizing additional code only within the main startup script. Ultimately, the precisions of both our puff and sound output are comparable to expensive, available systems such as the Habitest Modular system in conjunction with Coulbourn Graphic State 4 software, which itself offers 1 ms precision (<http://www.coulbourn.com/v/vspfiles/assets/manuals/Graphic%20State%204%20Users%20Manual.pdf>) , making the Teensy a viable, inexpensive alternative.

**Conclusion and Discussion**

We demonstrate the use of Teensy 3.2 microcontroller in integrating sCMOS camera with various devices for behavioral experiments. In one example, we utilized recently developed ADNS-9800 gaming sensors for precise and high speed locomotion tracking, along with simultaneous camera commands. In a second experiment, we commanded four devices with precise timing during a trace conditioning experiments. In both expriments, the timing of the Teensy interface was within 30us, suggesting the capablity of performing recording at 1000Hz? We developed user-friendly software interface, and simple hardware designs for both experiments. Together, these software and hardware configuration can be immediately adopted for the designed behavioral experiments, or customed for other types of behavioral experiments, where camera based imaging is desired during behavior. This platform additionally are low cost and can be easily scaled for parallel experiments across many animals, or further customized for various types of behavioral experiments.

We also demonstrate a setup built to implement a trace conditioning paradigm. In addition to requiring accurate alignment of imaging with behavior, operant conditioning paradigms need reliable stimulus timing. In this setting, repetition of stimulus and response must occur in a highly regular temporal fashion in order for a mouse to learn and in order for the neuronal response to be consistent. This illustrates the ability of the Teensy to orchestrate different classes of output—analog and digital, both long and short pulses—simultaneously and with high temporal accuracy while simultaneously sending out regular digital pulses to control an image capturing device. It also highlights the ability of this device to simultaneously produce an analog output, in particular to generate a sound, while performing other actions. As previously stated, a major advantage of the Teensy 3.2 over other microcontrollers such as the Arduino is the fact that it can output a true analog signal, whereas the Arduino UNO, for example, is capable only of outputting pulse-width modulated signals. This opens a venue for many experimental additions, particularly the addition of sound, without the need of extra devices such as resistors and capacitors to create an analog-like signal. Rather, the Teensy 3.2 simply needs to be soldered on to a paired hardware module (prop shield), and less in-depth knowledge about electronic circuits is necessary. In addition, it has a built-in “Audio” library that simplifies sound synthesis, reading, and mixing, all at 44.1 kHz which is stereo quality.

An important discovery during development of this system is that realization of a slight linear drift of the Teensy processing clock. This drift is linear in nature, which makes it simple to calibrate out if actual sub-µs precision to real world timing is essential. Further, it actually underscores the necessity of a central controller for precise acquisition and total experimental control. Synchronizing different devices only by a single pulse at the start of an experiment can lead to problems when trying to acquire motor output or deliver some experimental stimulus and examine cellular behavior with high temporal accuracy. Initiating experimental events from a high-level source, such as directly from a PC, can introduce timing jitter due to the multitude of tasks that a PC must attend to at any given point in time. For example, a recent calcium imaging study in the striatum finds additional neurological structure related to motor activity on very short timescales, but finds only velocity correlated with neural activity on longer timescales (Markowitz, et al., 2018). This suggests that with sufficient timing jitter, correlations on short time scales could be missed, yielding the conclusion that velocity is the only correlate of neural activity in the striatum.

Further, with concomitant imaging, one must also align tasks to imaging data after the fact, or face substantial variability in frame spacing. As explained previously (D'Ausilio, 2012; Solari, Sviatkó, Laszlovsky, Hegedüs, & Hangya, 2018), using a microcontroller such as an Arduino or Teensy 3.2 circumvents the issue of imprecise timing of behavioral events. We note that in addition, synchronizing camera triggers with experimental events circumvents the need of post-hoc image alignment.

In conclusion, Arduino UNO and the Teensy 3.2 both potentially fulfill these requirements, though additional timing functions, such as the “IntervalTimer” and “elapsedMicros”, make the Teensy 3.2 better suited for the particular task of delivering the equally spaced, regular digital pulses needed for triggering image capture. Finally, the precision and utility of the Teensy microcontroller make this a user-friendly, easily adaptable, accurate, and precise tool for different experimental designs in neuroscience in general, and particularly for imaging studies.

**Figures**

**Figure 1.** Diagrams of the two experimental device setups using Teesy interface. A, a floating, spherical treadmill setup for locomotion recording (A), **A** This experimental design consists of a Teensy 3.2 connected to two ADNS-9800 sensors and a CMOS camera, via serial-peripheral interfaces and a coaxial cable via SMA connectors, respectively. Every 50 milliseconds, a digital pulse triggers the CMOS camera to capture an image while simultaneously acquiring motor data from both ADNS sensors and sending them via a USB to a PC. The PC initiates each experiment by sending serial data consisting of the length of the experiment and imaging frequency to the Teensy. **B** a tone/light and puff trace conditioning setup.This experimental design constitutes a classic classical-conditioning paradigm. The user specifies via MATLAB or via a different interface the length and number of experimental trials. This information is sent via a USB to the Teensy 3.2, which initiates the experiment. In each trial, the Teensy initiates a 9500 Hz tone at 44.1 kHz while turning on a light. These stimuli are followed by an air puff, also delivered via the Teensy. In order to generate a sound loud enough for the speaker, the Teensy is soldered to a prop-shield, which contains an amplifier. The Teensy 3.2 sends time stamps, trial, and stimulus information via the USB back to the PC.

**Figure 2. …need a summary title here.A.** A schematic demonstrating the wiring connections between a Teensy 3.2, prop shield, and an external speaker. Dotted lines indicate solid connections. All connections between the Teensy 3.2 and prop shield were made using 14x1 double insulated pins, and the output to the speaker from the prop shield was made using regular wire and a coaxial cable. Some extraneous and unused pins on the Teensy and the prop shield were not included in this diagram. **B.** A schematic demonstrating the wiring of Teensy to two ADNS-9800 sensors via serial peripheral interface connections (SPIs). Solid dots at intersections between lines indicate connections. Some unused pins on the Teensy 3.2 were not included in this schematic.

**Figure 3.** **…need a summary title here A.** Part of a sample 10 minute recording session during which a head-fixed animal was allowed to run on the three-dimensional treadmill. Shown in **Figure 1A**. The mouse’s average speed was 7.1 + 6.9 cm/s, with a maximum velocity of 47.0 cm/s, within ranges reported elsewhere. **B.** Times of digital pulses sent by the Teensy 3.2 as measured internally by the Teensy, vs times of the digital pulses as measured by an external device. Green indicates linear model, and in black are experimental data, down-sampled by a factor of 200. The linear model estimates a slope of 1.000028927 + .000000005 (t(11997)= 2.0381e+08, p < 0.001, R2=1; intercept = 0.000107 + 0.000002, t(11997) = 63.243, p < 0.001), indicating an excellent fit and very nearly a 1:1 correspondence of time stamps.

**Figure 4.** title…**A.** Timing of the digital pulses as measured by the Teensy 3.2 in the tone/light-puff setup versus timing as measured by an external device. These measurements have a correspondence near 1:1 (R2=1, slope: 1.0000334 + 0 (to machine precision), t(14998)=infinite, p<0.001). **B.** Timing measured by the teensy for (i) and by the TDT system for (ii-iv) over the course of fifty trials; (i) shows the latency between the theoretical onset of the tone and the measured timing of the tone as measured by the TDT device (mean=7.6 + 0.9 ms, range=2.9 ms); (ii) shows the consistency of the length of tone intervals across all trials (mean=700 + 1 ms, range=2.9 ms); (iii) shows the consistency of the latency of the tone stimulus interval, as measured by the TDT sytem (mean= -0.004 + 0.012 ms, range=0.04 ms); (iv) shows the consistency of the length of the puff across all trials (mean = 100.03+0.02 ms). (all + std).

**Tables**

Table 1. Specialty components necessary to build a motor output system

|  |  |  |  |
| --- | --- | --- | --- |
| **Part name** | **Website** | **Part number** | **Cost per unit** |
| Teensy 3.2 | https://www.pjrc.com/store/teensy32.html | TEENSY32 | $19.80 |
| ADNS-9800 sensors | https://www.tindie.com/products/jkicklighter/adns-9800-laser-motion-sensor/ | None | $27.50 |

Table 2. Specialty components necessary to build a tone/light-puff system.

|  |  |  |  |
| --- | --- | --- | --- |
| **Part name** | **Website** | **Part number** | **Cost per unit** |
| Teensy 3.2 | https://www.pjrc.com/store/teensy32.html | TEENSY32 | $19.80 |
| 14x1 Double insulator pins | https://www.pjrc.com/store/header\_14x1\_d.html | HEADER\_14x1\_D | $0.85 |
| Prop shield | https://www.pjrc.com/store/prop\_shield.html | PROP\_SHIELD | $19.50 |

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