An inexpensive wireless video recording system for continuous behavioral observations

W.David Weber[1]* & Heidi S. Fisher[1]

[1] Biology Department, University of Maryland, College Park, MD

* Corresponding author

E-mail: wweber@umd.edu

Abstract

Video recording technology is an important tool in the field of animal behavior, by producing a record of experiments, interactions, and contextual information, and by reducing observer effects; but video recording systems remain cost prohibitive for many researchers. Here we present an inexpensive method for building a wireless video recording system to continuously monitor behavioral or other biological experiments. Our system employs Raspberry Pi computers and cameras, open-source software, and allows for remote operation, live-streaming, and the capacity to simultaneously record from several cameras in an array. To validate our system, we continuously monitored home-cage behavior in the California mouse (*Peromyscus californicus*) in a laboratory setting. To record behaviors of this nocturnal species, we captured video in both low- and bright-light environments. We then quantified mating interactions of California mouse pairs by analyzing the videos with an open-source event logging software. Our video recording platform offers users the flexibility to modify the specifications for a range of tasks beyond animal behavior experiments. Moreover, this low cost, flexible and scalable, wireless video recording system offers a tool to make research more efficient and reliable to a larger population of scientists.

Introduction

Behavior often represents an animal's most immediate and dynamic response to internal or external cues [1]. Thus, behavioral data are invaluable indicators of change, yet the complexity and diversity of behaviors can be challenging to quantify. Traditional sampling methods from live observations (e.g., scan sampling, focal animal sampling, one-zero sampling [2-3]) frequently results in an estimate, rather than a precise measure of behaviors, or only provides data from a subset of subjects or interactions within a social group [4]. The behavioral record is therefore often incomplete with live observational data, and the presence of an observer can influence the behavior of study subjects, thus biasing the results [5–7]. Moreover, to fully understand an animal's response, it is imperative to understand the context and the environment in which the behavior was expressed. Video recording enables researchers to review behaviors multiple times to yield a more complete dataset, reduces observational biases, and can capture contextual information.

Video recording has become a nearly ubiquitous tool for behaviorists and useful in a wide range of studies. For example, video can improve data collection in manipulative behavioral assays from studies of visual recognition in cichlids [8] and foraging in fruit flies [9], to parental care [10] and anxiety in rodents [11]. Moreover, passive monitoring approaches, such as home-cage cameras, can be used to record social behaviors, such as pair bonding in marmosets [12], or mating in whiteflies [13], guppies [14], and gerbils [15]. Outside of the lab, passive monitoring with nest box cameras have revealed unexpected behaviors including paternal care in tree swallows, even when extra-pair copulations were evident to the male [16], personality traits and social dominance in zebra finch [17], and long-term social interactions in "near natural" enclosures in house mice [4]. Continuous video recording systems provide a record of behavior and contextual information in a variety of studies from controlled laboratory assays to passive monitoring in the wild.

With few exceptions, continuous video recording improves rigor and repeatability in all behavioral studies, yet the technology remains cost prohibitive for researchers with limited funding or for complex experimental designs requiring numerous cameras. Here we present an inexpensive method for building a wireless video recording system using-source software that allows for remote operation, live-streaming, and the capacity to simultaneously record from several cameras to create an array. We then present validation of this system, in which we built an array of modules to continuously record mating behavior in California mice, *Peromyscus californicus*.

Materials and Methods

We constructed a video recording array using Raspberry Pi (RPi; Caldecote, Cambridge, UK) modules and-source software to continuously record multiple mating pairs of captive California mice (*Peromyscus californicus*) across several reproductive cycles. We then transferred the video files to Google Drive (Google LLC, Mountain View, CA, USA) for cloud-based storage, and later scored videos using the free open-source software, BORIS (Behavioral Observation Research Interactive Software [18]).

Recording module assembly

Raspberry Pi computers are very small, inexpensive computers that offer a flexible platform to build a video recording system. Some base units can be purchased with cameras but storage and cables must be purchased separately. Table 1 describes the basic starting materials we used and ordering information. At the time of purchase, each recording module cost roughly $60.00 to build.

Table 1. Basic Materials

Product	Comments
64 Gb micro SD card	A larger card can be purchased if the budget allows; be sure the card comes with a SD card adaptor.
Raspberry Pi Zero(W)	The “W” version must be purchased for WiFi connectivity.
Raspberry Pi NoIR Camera	
Pi Foundation Official Pi Zero Case (Pi Zero Case)	This is the case for the assembled components.
Micro HDMI charging cable	
Charging dock	A multiple port dock is advised if using multiple recording devices.
USB Hub	

To build a recording module, we first loaded all application files, including an operating system (OS), onto a micro SD card. We used 64 Gb micro SD cards, as roughly 8 Gb must be allocated to the OS and our video files averaged 30 Gb in size. We formatted the card as MS-DOS(Fat); the “Raspbian” OS used in this application was designed to be loaded onto cards smaller than 32 Gb, therefore the 64 Gb card required reformatting. Once formatted, we loaded the “Raspbian” OS (https://www.raspberrypi.org/downloads/noobs/) onto the card and then installed it into the micro SD card port of a Raspberry Pi Zero(W) board (Figure 1A).

Next, we attached the Raspberry Pi NoIR camera to the R-Pi board (Figure 1B) and placed the board into the Pi Zero Case (Figure 1C). This step requires extreme care, as there are locking pins (see arrows in Figure 1D) that secure the board and camera to the case, thus it was necessary to bend the case to prevent damaging the R-Pi board. Once the case was closed, the recording module was complete (Figure 1D). We next attached the recording module to a monitor, mouse and keyboard with a USB hub, and then connected the module to a power source to activate the unit. The OS automatically initializes as soon as power is connected, the activation process runs for approximately 10 minutes and then the Raspian desktop appears.

Figure 1. Assembly of a recording module. (A) MicroSD card installed into a Raspberry Pi Zero(W) board. Grey arrow indicates the location of the MicroSD card port. (B) Raspberry Pi

board is attached to the camera assembly. (C) Pi Zero Case. Grey arrows indicate locking pins that the board and camera must fit underneath. (D) An assembled recording module.

Recording Module Programming

On every module, the default username is “pi” and password is “raspberry”, making them susceptible to unauthorized off-network access. Therefore, we next reset the default username and password in the “Raspberry Pi Configuration Menu”. Under the interface tab of that same menu, we then enabled the “Camera”, selected “SSH” (allows for remote access) and “VNC” (allows for remote file sharing) options, and then we rebooted the module. After reboot, we established an internet connection by hovering the curser over the WiFi icon, selected the appropriate network, and logged in. By hovering the curser over the WiFi icon after establishing a connection, the IP address is revealed; with this IP address we could remotely log into the module using RealVNC Viewer (https://realvnc.com/en/), an open-source software.

Behavioral Observations

To assess the routine use of the recording module to record social interactions, we observed mating behavior in California mice, *Peromyscus californicus*. We originally obtained four male and four female mice from the Peromyscus Genetic Stock Center at the University of South Carolina (https://www.pgsc.cas.sc.edu/), and housed them at the University of Maryland, in accordance with the Institutional Animal Care and Use Committee policies (protocol number: R-Jul-18-38), and in standard transparent laboratory rodent cages lined with cedar shavings. We provided food and water *ad libitum* and maintained all mice at 22°C in a 16:8 light-dark cycle, simulating this species’ breeding season [19].

To record the mating behavior, we placed a male and a female into a cage on a camera rack. Camera stands can be easily purchased online or 3D printed, but we fashioned camera racks from metal shelving on which we attached two blocks cut from recycled styrofoam at either end to hold the two recording modules per cage (see below), in the middle of which we

153 placed a cage (Figure 2). We recorded from four pairs, each with their own pair of recording
154 modules. We recorded behaviors during the light period with one module and used a second
155 module to record behavior during the dark period while the room was illuminated with red lights
156 and inferred LED lights. We found that using two modules, each set at different parameters
157 optimized for each light environment, was the most effective way for us to obtain high quality
158 video across the entire light-dark cycle.
159
160 **Figure 2. Assembled camera rack with animal cage**.
161
162 Next, we remotely logged into the modules using a Python 3 shell (selected from the
163 programming menu on the Raspbian desktop) and executed the camera script (Table S-1; all
164 coding scripts described in this article can also be accessed at
165 https://github.com/wdavidweber/Pi-Recording-Module). To send video files directly to a Google
166 Drive folder, we used an additional script because the software is not included in the Raspian
167 OS. Using the terminal console in Raspbian, we uploaded the "rclone" (Nick Craig-Wood ©
168 2012) open-source software (Table S-2). We regularly monitored the modules and Google Drive
169 folders to make sure that data was uploaded correctly. To score the behaviors in BORIS, we
170 converted the .h264 format files (the default Raspbian filetype) into ".mp4" format using the
171 "ffmpeg" package, available in the Raspbian OS (the code for this is the last line of script in
172 Table S-1). We performed the file conversion using a High-Performance Computing Cluster at
173 the University of Maryland because our video files were too large to be converted on the
174 modules. When necessary, we live-streamed footage with a YouTube account
175 (https:www.youtube.com/) by loading "Docker" onto the module (Table S-3). With this method,
176 video recording and live-streaming cannot be accomplished simultaneously.
177 To quantify mating behavior, we scored videos using the open-source software, BORIS,
178 and developed an ethogram based on the work of Dewsbury [20]. We recorded the frequency of

mounts, intromissions, and ejaculations, as well as intromission latency (the time between the start of a reproductive bout and the first intromission), ejaculation latency (the time between the first intromission and the subsequent ejaculation), post-ejaculatory interval (the time between an ejaculation and the beginning of the next copulatory bout), reproductive event (the total duration of all mating events during a female's single reproductive period, beginning with the first mounting event and concluding with the last ejaculation), copulatory bout (the duration between the first mounting event and the first ejaculation).

Results

We continuously recorded home-cage behavior for three weeks from four pairs of California mice. In total, we collected 2016 hours of video, which resulted in roughly 2 TB of data. Recording one hour of footage during the light period (Figure 3A-B), at a resolution of 1280x768, a framerate of 15 frames per second, and a brightness value of 70, resulted in recordings that were 440 Mb to 500Mb in size. Recording one hour of footage during the dark period (under red lights and LED inferred lights; Figure 3C-D) at a resolution of 1280x768, a framerate of 15 frames per second, and a brightness value of 80, resulted in recordings of 1.5Gb to 2Gb in size. Reducing the preset parameters for resolution, framerate, or brightness resulted in smaller files, but less resolved footage.

Figure 3. Recording module array and output. (A) The array during the dark period with room illuminated by red lights and inferred LED lights over the cages. (B) The same array in (A) but from the other side while during the light period. Note the LED lights mounted on wall above cages. (C) Still image of a video obtained during the dark period. (D) Still of a video obtained during the light period.

We scored mating behavior from the one pair that successful produced a litter after the mating trial. The active mating period spanned a total of 5 hours, 24 minutes, and 3 seconds of

footage, all of which occurred during the dark period of the photocycle and included two copulatory bouts. The first mating bout spanned 4 minutes, 15 seconds, and included 8 mounts, 3 intromissions and a single ejaculation; spanned 2 minutes, 45 seconds and included 6 mounts, 5 intromissions and a single ejaculation. We found that the mean intromission latency was 1 minute 49 seconds and the mean ejaculation latency was 1 minute 42 seconds. The two copulatory bouts were separated by a 36 minutes 39 second refractory period.

Discussion

Here we describe a wireless video recording system to remotely monitor animal behavior. This tool permits user-determined specifications, including live-streaming and multiplexing, and has the capacity to simultaneously record and upload data files to storage. Moreover, this system allows for continuous behavioral monitoring on a flexible timescale. The cost of the recording module that we describe is comparable to some pre-assembled commercial surveillance cameras, which like the RPi recording module, often use SD cards to store footage and may provide cloud storage for a fee with restricted allocations. Therefore, while our system is not unique, we found that it offered a wider range of low-cost modifications to suit a variety of research environments by incorporating open-source software add-ons.

For validation purposes, we used the video capture system we report here to record, and subsequently quantify, mating behavior in the California mouse. Once we positioned the cameras in place in our animal facility, we controlled the modules from our laboratory located in another building. This design eliminated possible observer effects on the animals' behavior, provided contextual information on the animals' environment, and allowed for off-hours monitoring of the animal housing space. Furthermore, with the addition of red room lights and inferred LED lights, we were able to record mating behavior of this nocturnal species without interruption or disturbance.

In the research setting, our video recording system can be applied to tasks beyond animal behavior experiments. For example, this system could be used to remotely monitor chemical reactions or other assays in which timing is uncertain, or if housed within an incubator, to monitor bacterial or embryo culture. The flexible platform, scalability and low cost of our “do it yourself” wireless video recording system is a powerful lab tool to make research more efficient and reliable to a larger population of scientists.

Acknowledgements

We thank Andrés Bendesky, whose use of Raspberry Pi cameras to record parental care behavior in *Peromyscus* inspired us to build and report on the system presented here. We also thank Irene Lui for her computer programming guidance, Erica Glasper for the experimental animals, and R. Zaak Walton, whose thoughtful discussion and advice was essential to this project.

References

1. Bretman A, Gage M, Chapman T. Quick-change artists: male plastic behavioural responses to rivals. Trends Ecol Evol. 2011;26(9):467–73.
2. Altmann J. Observational Study of Behavior : Sampling Methods. Behaviour [Internet]. 1974;49(3/4):227–67.
3. Martin P, Bateson P. Measuring behaviour: An introductory guide. 2nd, editor. Cambridge, EN, UK: Cambridge University Press; 1995.
4. Weissbrod A, Shapiro A, Vasserman G, Edry L, Dayan M, Yitzhaky A, et al. Automated long-term tracking and social behavioural phenotyping of animal colonies within a semi-natural environment. Nat Commun. 2013;4(May):1–10.
5. Wilson S. The use of ethnographic techniques in educational eesearch. Rev Educ Res. 1977;47(2):245–65.

6. Monahan T, Fisher J. Benefits of “observer effects”: Lessons from the field. Qual Res. 2010;10(3):357–76.

7. Herbert R, James F. The Hawthorne experiments: first statistical interpretation. Am Sociol Rev. 1978;43(5):623–43.

8. Escobar-Camacho D, Marshall J, Carleton K. Behavioral color vision in a cichlid fish: *Metriaclima benetos.* J Exp Biol [Internet]. 2017;220(16):2887–99.

9. Jang EB, Light DM. Behavioral responses of female oriental fruit flies to the odor of papayas at three ripeness stages in a laboratory flight tunnel (*Diptera: Tephritidae*). J Insect Behav. 1991;4(6):751–62.

10. Bendesky A, Kwon YM, Lassance JM, Lewarch CL, Yao S, Peterson BK, et al. The genetic basis of parental care evolution in monogamous mice. Nature

11. Leuner B, Glasper ER, Gould E. Sexual experience promotes adult neurogenesis in the hippocampus despite an initial elevation in stress hormones. PLoS One. 2010;5(7).

12. Gerber P, Schnell C, Gusti A. Behavioral and cardiophysiological responses of Common Marmosets (*Callithrixjacchus*) to social and environmental changes. Primates. 2002;43(July):201–16.

13. Ruan YM, Luan JB, Zang LS, Liu SS. Observing and recording copulation events of whiteflies on plants using a video camera. Entomol Exp Appl. 2007;124(2):229–33.

14. Pilastro A, Mandelli M, Gasparini C, Dadda M, Bisazza A. Copulation duration, insemination efficiency and male attractiveness in guppies. Anim Behav. 2007;74(2):321–8.

15. Prates EJ, Guerra RF. Parental care and sexual interactions in Mongolian gerbils (*Meriones unguiculatus*) during the postpartum estrus. Behav Processes. 2005;70(2):104–12.

16. Whittingham L, Dunn P, Robertson R. Confidence of paternity and male parental care: an experimental study in tree swallows. Anim Behav. 1993;139–47.

17. Morgan D, Auclair Y, Cezilly F. Personality predicts social dominance in female zebre finches, *Taeiopygia guttata*, in a feeding context. Anim Behav. 2011;81(1):219–24.

18. Friard O, Gamba M. BORIS: a free, versatile open-source event-logging software for video/audio coding and observations. Methods Ecol Evol. 2016;7(11):1325–30.

19. Kirkland GL, Layne JN. Advances in the study of *Peromyscus* (*Rodentia*). Lubbock, TX, USA: Texas Tech University Press; 1989.

20. Dewsbury D. Copulatory behavior of White-Footed mice (*Peromyscus leucopus*). J Mammal. 1975;56(2):420–8.

Supplemental Material Captions

Table S-1. Camera operation and recording script

Table S-2. Rclone installation and GDrive connection script

Table S-3. Docker script for live-streaming

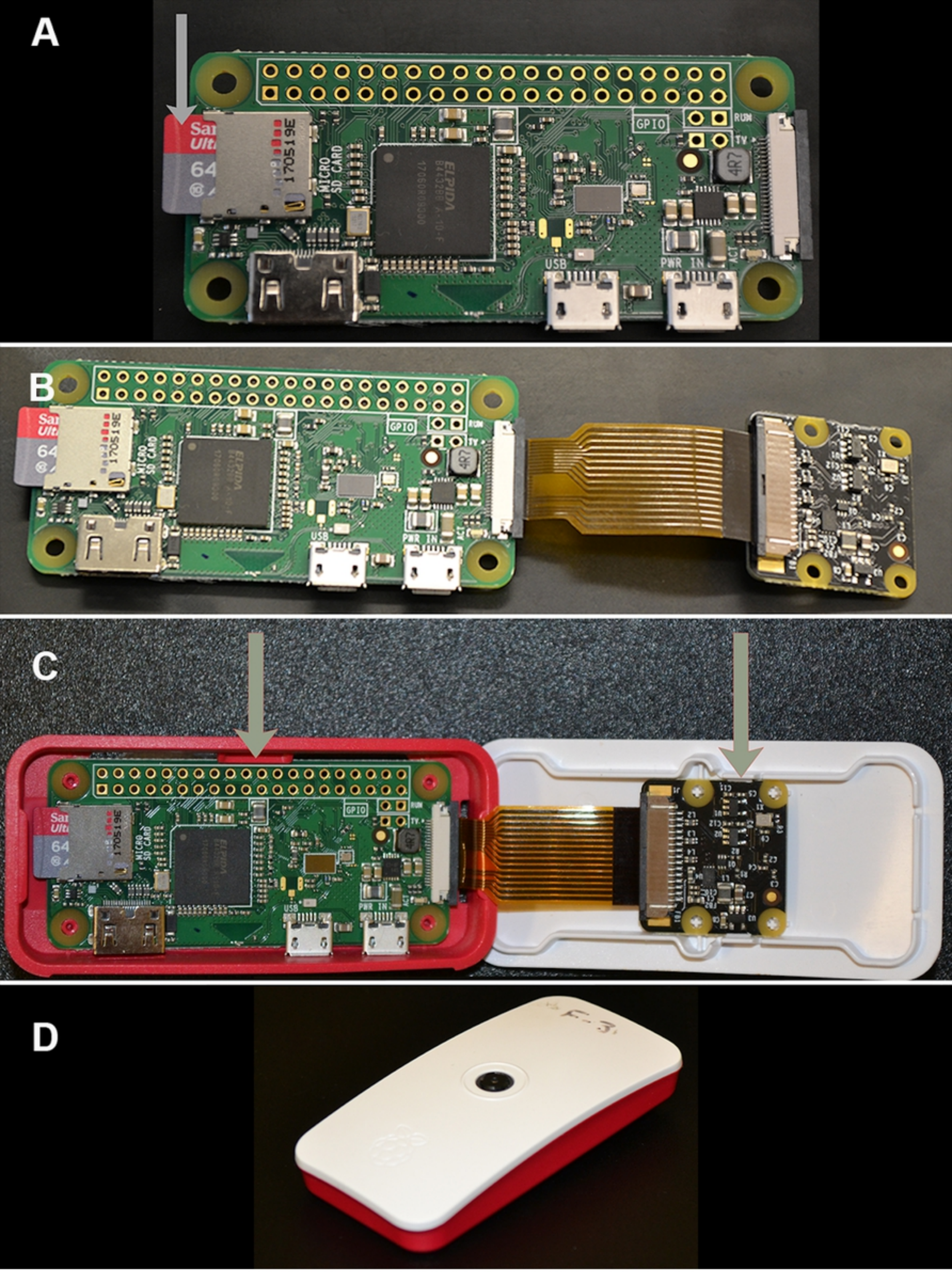

Figure 1

Figure 2

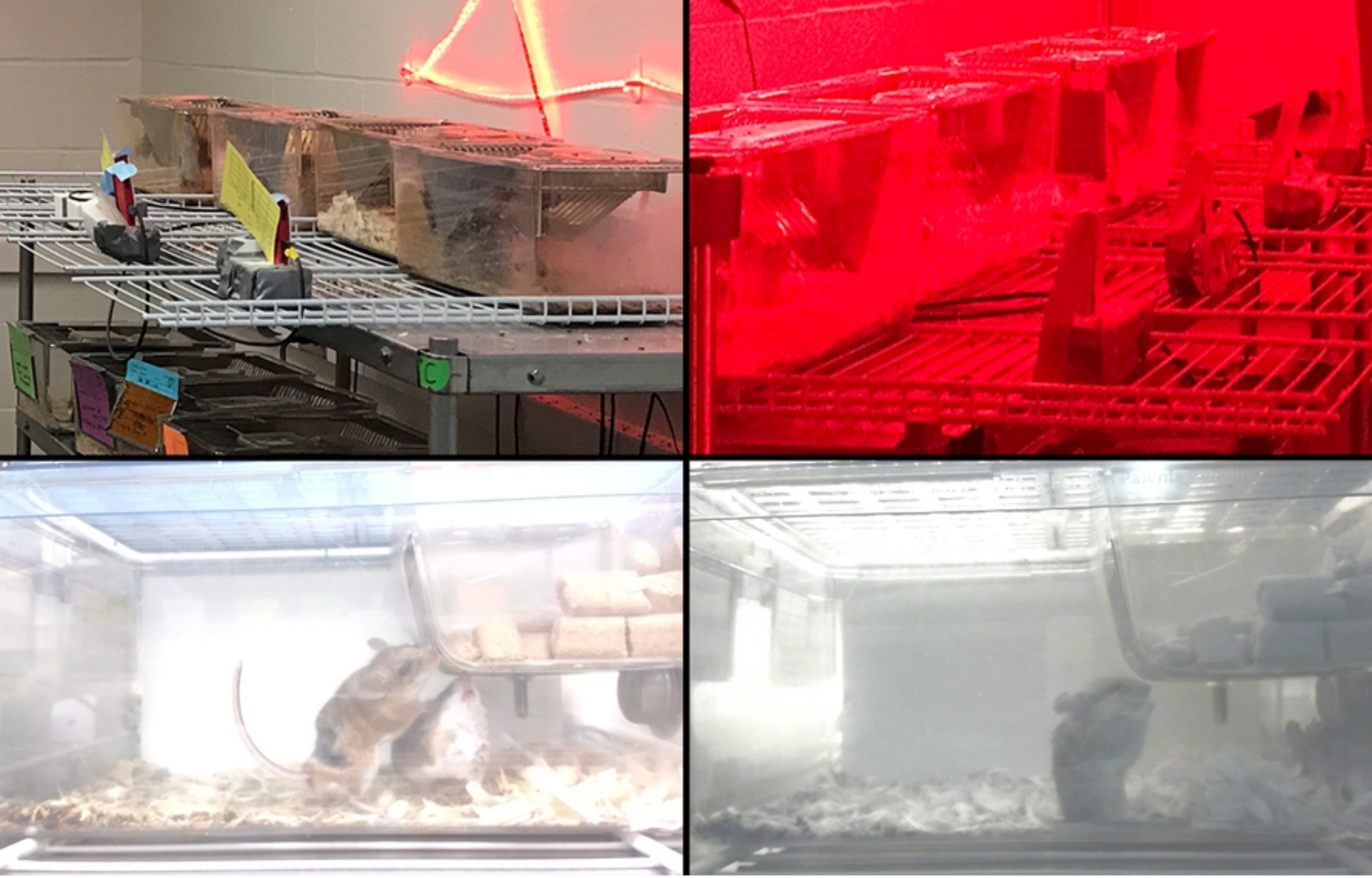

Figure 3