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RIGBOX: AN OPEN-SOURCE TOOLBOX FOR PROBING NEURONS AND BEHAVIOR

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Setting up an experiment in behavioral neuroscience is a complex process that is often managed with ad hoc solutions. To streamline this process we developed Rigbox, a high-performance, open-source software toolbox (github.com/cortex-lab/Rigbox). Rigbox simplifies the interfacing of hardware and software, synchronizes data streams from multiple sources, manages data via communication with a remote database, implements a viewing model for visual stimuli, and creates an environment where experimental parameters can be easily monitored and manipulated. The toolbox facilitates a modular approach to designing experiments. Rigbox runs in MATLAB, with Java components to handle network communication, and a C library to boost performance. Its main submodule, Signals, allows intuitive programming of behavioral experiments. Here we illustrate its function with two interactive examples: a human psychophysics experiment, and the game of Pong. We give an overview of the other packages in Rigbox, provide benchmarks, and conclude with a discussion on the extensibility of the software and comparisons with similar toolboxes.

INTRODUCTION

In behavioral neuroscience, much time is spent setting up hardware and software and ensuring compatibility between them. Experiments often require configuring disparate software to interface with distinct hardware, and integrating these components is no trivial task. Furthermore, there are often separate software components for designing a

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behavioral task, running the task, acquiring and processing the data, and logging the data. This requires learning the fundamentals of each software package, and how to make them communicate appropriately.

For example, in a typical experiment focused on decision-making, an experimental subject chooses a stimulus amongst a set of possibilities and obtains a reward if the choice was correct (e.g. Carandini and Churchland, 2013). This experiment requires software that starts and ends the experiment, presents the stimuli, delivers reward, etc. and software that acquires, processes and logs the experimental data, which could include stimulus and response history, body position, and concurrent neural data.

To address this variety of needs we designed Rigbox (github.com/cortex-lab/Rigbox). Rigbox is modular, high-performance, open-source software for implementing behavioral neuroscience experiments and acquiring experiment-related data. Principally, Rigbox facilitates recording, synchronizing, and managing data from a variety of sources. Furthermore, Rigbox promotes bespoke behavioral task design via a framework called Signals, which exploits both object-oriented and functional reactive programming paradigms to allow an experimenter to intuitively define and parameterize an experiment.

METHODS AND RESULTS

We begin by giving a general overview of Rigbox. We go on to describe Signals, the core package of Rigbox, and provide two interactive examples of its use, a simple experiment in visual psychophysics and the game of Pong. We then briefly describe the other packages in Rigbox, and provide benchmarking results.

Overview

Rigbox is made up of a number of packages which run on two computers, referred to as the “Master Computer” (MC) and “Stimulus/Slave Computer” (SC) (Figure 1). MC is responsible for selecting, parameterizing, starting, and monitoring an experiment via a MATLAB GUI. SC is responsible for running an experiment on a rig and interacting with that rig’s hardware during runtime. MC can control multiple SCs simultaneously.

MC and SC communicate during runtime via Java WebSockets using TCP/IP. Therefore, it is necessary for both computers to be connected to high-speed internet. The precise computer hardware requirements for SC depend on the complexity of the experiment, and for MC depend on the number of experiments run concurrently (i.e. number of

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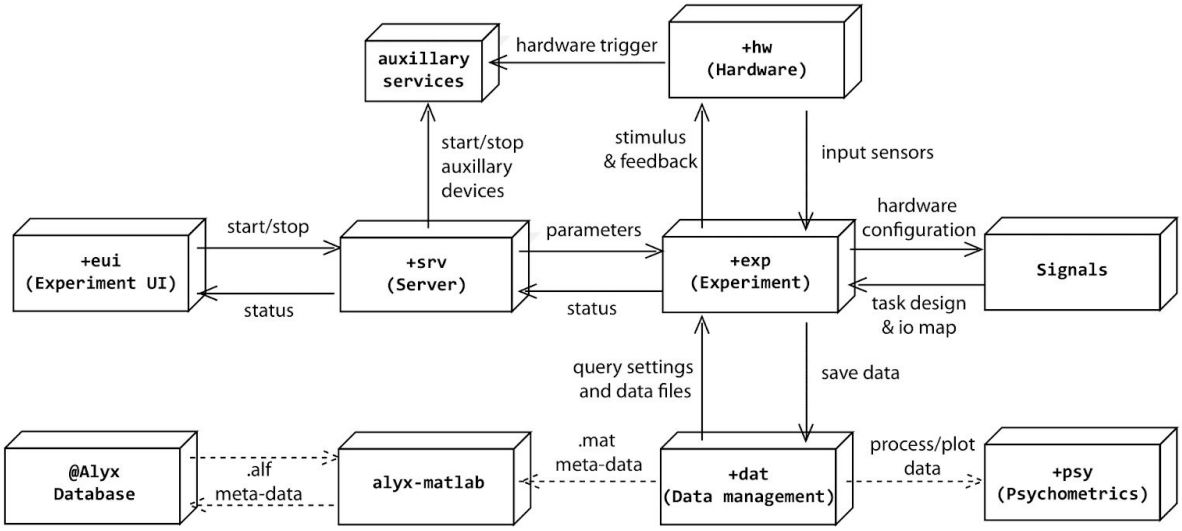

Figure 1. Schematic of Rigbox package interactions. The solid lines represent necessary communication between Rigbox packages, and the dashed lines represent optional communication (for saving data to a remote Alyx database, and for processing/plotting data). The *+eui* package runs a GUI on the master computer (MC), and the *+srv* package launches stimulus presentation on the stimulus computer (SC). Though this figure shows only one direct MC-SC connection, MC can control multiple SCs simultaneously.

active SCs controlled). For most experiments, typical modern desktop computers running Windows will suffice. SC also requires input/output device(s) for polling hardware inputs and triggering hardware outputs, and optionally requires graphics and sound cards, depending on the complexity of the stimuli to be presented.

Instructions for installation and configuration can be found in the `README` file and the `docs\setup` folder of the GitHub repository. This includes information on required dependencies, setting data repository locations, configuring hardware, and setting up communication between the MC and SC computers.

Signals

Signal was designed for building bespoke behavioral tasks. The framework is built around the paradigm of functional reactive programming, which simplifies problems that deal with change over time (Lew, 2017). Signals represents an experiment as a reactive network whose nodes (“signals”) represent experimental parameters. These signals can evolve over time through interactions with each other. The framework provides a set of input signals which represent time, experiment epochs, and hardware input devices, and a set of output signals which represent hardware output devices.

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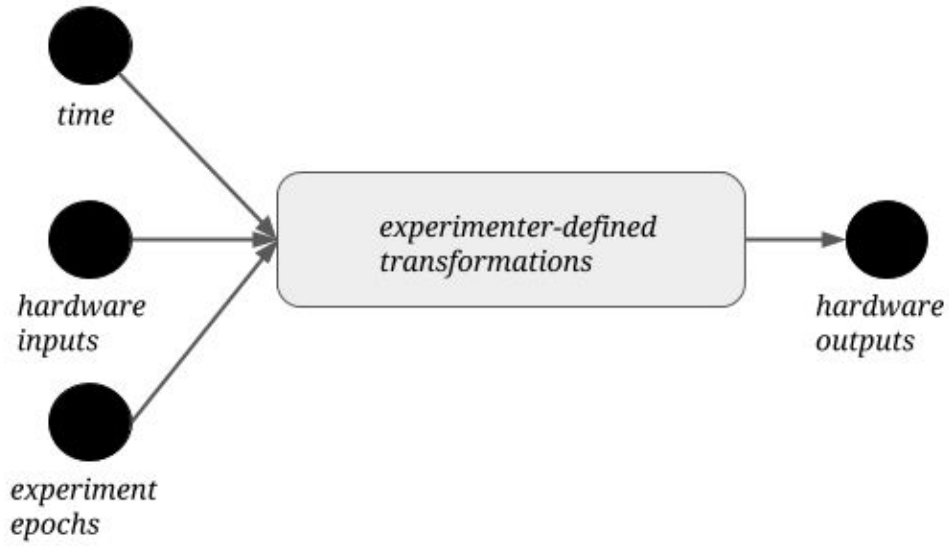

Figure 2. A Signals representation of an experiment. There are three types of input signals in the network, representing time, hardware inputs (such as an optical mouse, keyboard, rotary encoder, lever, etc.), and experiment epochs (such as trial and experiment start and end conditions). The experimenter defines transformations that create new signals from these input signals (not shown), which ultimately drive hardware outputs (such as a reward valve, blow gun, galvanometer, etc.).

Thus, an entire experiment can simply be thought of as a network which maps hardware inputs to hardware outputs via a set of experimenter-defined transformations (Figure 2).

The core goal of Signals is to represent the relationship between experimental parameters with straightforward, self-documenting operations. For example, to define the temporal frequency of a visual stimulus - for example, a drifting grating - an experimenter could create a signal which changes the stimulus' phase as a function of time (Figure 3). This is shown in the code below:

```
theta = 2*pi; % angle of phase in radians
freq = 3; % frequency of phase in Hz
stimulus.phase = theta*freq*t; % phase that cycles at 3 Hz for given stimulus
```

The operations that can be performed on signals are not just limited to basic arithmetic. A number of built-in MATLAB functions (including logical, trigonometric, type conversion, and array operations) have been overloaded to work on signals as they would on basic numeric or char types. Furthermore, a number of classical functional programming functions (e.g. "map", "scan", etc…) can be used on signals. These endow signals with memory, and allow them to gate, trigger, filter and accumulate other signals (Figure 4).

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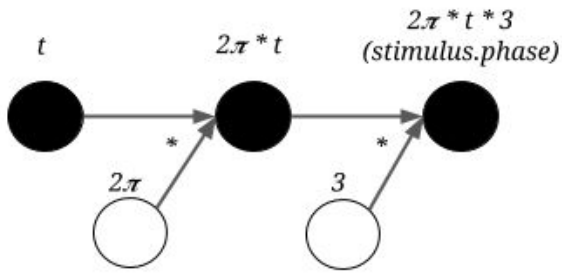

Figure 3. Representation of the time-dependent phase of a visual stimulus in Signals. An unfilled circle represents a constant value - it becomes a node in the network when combined with another signal in an operation (in this instance, via multiplication).

With this powerful framework, an experimenter can easily define complex relationships between input and output devices (or more abstractly, between stimuli, response and reward) in order to create a complete experiment protocol. This protocol takes the form of a user-written MATLAB function, which we refer to as an "experiment definition" ("exp def"). Signals runs an experiment by loading this exp def into a network and posting values to the network's input signals on every iteration of a while loop, which triggers asynchronous propagation through the reactive network. The experiment ends when the "experiment stop" signal is updated (e.g. when a number of correct trials is reached, or when the experimenter presses the "end" button in the MC GUI).

The following is a brief overview of the structure of an exp def. An exp def takes up to seven input arguments:

```
function expDef(t, events, params, visStim, inputs, outputs, audio)
```

In order, these are 1) the time signal; 2) an events structure containing signals which define the experiment's epochs, and a set of user-chosen signals to be logged from those defined within the exp def; 3) a parameters structure to define session- or trial-specific signals whose values can be changed directly from a GUI before starting an experiment - parameter defaults are set within the exp def and parameter sets can be saved and loaded across subjects and experiments; 4) the visual stimuli handler which contains as fields all signals which parametrize the display of visual stimuli—any visual stimulus signal can be assigned various elements (which the viewing model allows to be defined in visual degrees) for being rendered to a screen, and a visual stimulus can be loaded directly from a saved image file; 5) an inputs structure containing signals which map to hardware inputs devices; 6) an outputs structure containing signals which map to

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hardware output devices; 7) the audio stimuli handler which can contain as fields signals which map to available audio devices.

Tutorials on creating an exp def, examples of working exp defs and standalone scripts (including those mentioned in this paper), and an in-depth overview of Signals can be found in the `signals/docs` folder within the Rigbox repository. Though running a Signals experiment in Rigbox typically requires two computers, the following examples can be run from a single Windows PC, as their only required hardware devices are an optical mouse and keyboard. Readers are encouraged to run these examples upon installing Rigbox and its necessary dependencies.

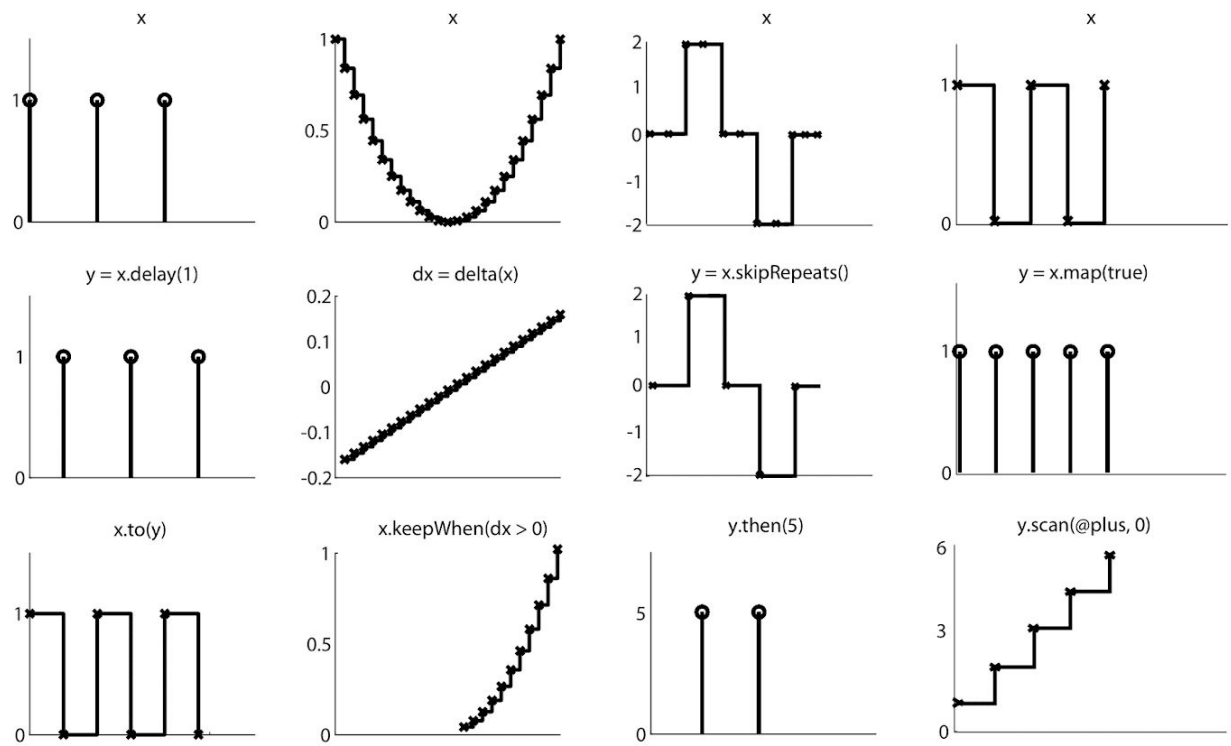

Figure 4. The creation of new signals via example signals methods. Conceptually, a signal can be thought of as both a continuous stream of discrete values, and as a discrete representation whose value changes over time. Each panel represents a signal. The x-axis represents time, and the y-axis represents the signal's value. Each column depicts a set of related transformations. The second row depicts a signal which results from applying an operation on the signal in the same column's first row. The third row depicts a signal which results from applying an operation on the signals in the same column's first and second rows.

Example 1: A Psychophysics Experiment

Our first example of a human-interactive Signals experiment is a script that recreates a

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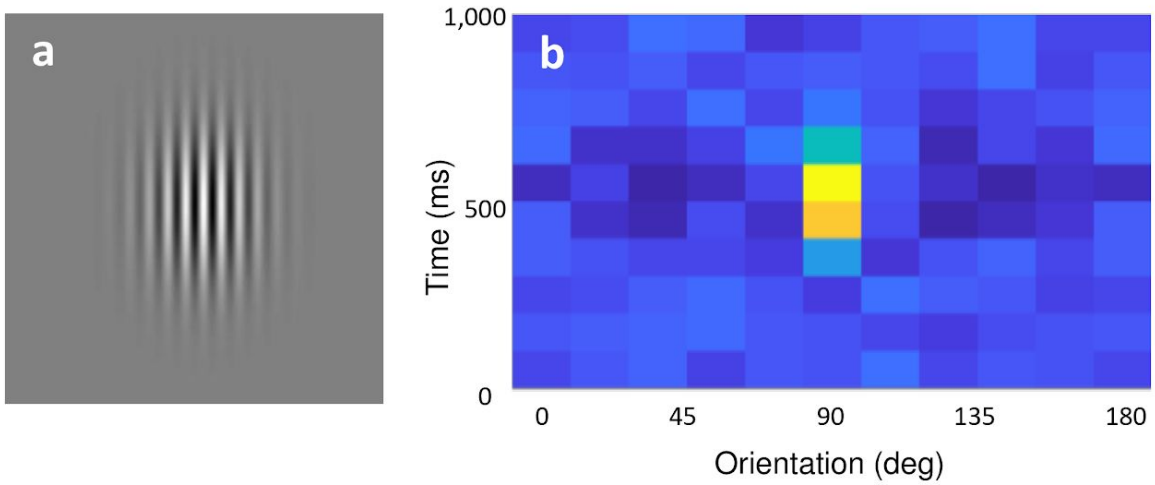

Figure 5. a) A sample grating for which the subject is required to respond to via a "ctrl" key press. **b)** A heatmap showing the grating orientations for the ten frames immediately preceding a "ctrl" key press, summed over all "ctrl" key presses for the duration of the experiment. After a few minutes, the distribution of orientations over time at a "ctrl" key press resembles a 2D Mexican Hat wavelet, centered on the orientation the subject was reporting at the subject's average reaction time. In this example, the subject was reporting a vertical grating orientation (90 degrees) with an average reaction time of roughly 600ms.

psychophysics experiment to study the mechanisms that underlie visual stimulus orientation discrimination in humans (Ringach 1998). In this experiment, the observer looks at visual gratings that change rapidly and randomly in orientation and phase (Figure 5a). The gratings change so rapidly that they summate in the visual system, and the observer tends to perceive two or three of them as superimposed. The task of the observer is to hit the "ctrl" key whenever the grating's orientation is vertical. At key press, the probability of detection is plotted as a function of stimulus orientation in the recent past. Typically, this exposes a center-surround type of organization, with orientations near vertical eliciting responses, but orientations further away suppressing responses (Figure 5b).

To run this experiment, simply run the `signals/docs/examples/ringach98.m` file in the Rigbox repository. Below is a complete breakdown of the thirty lines of code:

First, some constants are defined:

```
oris = 0:18:162; % set of orientations, deg
phases = 90:90:360; % set of phases, deg
presentationRate = 10; % Hz
winlen = 10; % length of histogram window, frames
```

Next, we create a figure and our Signals network:

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```
figh = figure('Name', 'Press “ctrl” key on horizontal grating',...
  'Position', [680 250 560 700], 'NumberTitle', 'off');
vbox = uix.VBox('Parent', figh);
[t, setElemsFun] = sig.playgroundPTB([], vbox);
net = t.Node.Net; % Handle to our network
axh = axes('Parent', vbox, 'NextPlot', 'replacechildren', 'XTick', oris);
xlabel(axh, 'Orientation');
ylabel(axh, 'Time (frames)');
ylim([0 winlen] + 0.5);
```

Now we wire our network:

```
% Create a signal from the keyboard presses
keyPresses = net.fromUIEvent(figh, 'WindowKeyPressFcn');
% Filter it, keeping only ‘ctrl’ key presses. Turn into logical signal
reports = strcmp(keyPresses.Key, 'ctrl');
% Sample the current time at presentationRate
sampler = skipRepeats(floor(presentationRate*t));
% Randomly sample orientations and phases
oriIdx = sampler.map(@(~)randi(numel(oris)));
phaseIdx = sampler.map(@(~)randi(numel(phases)));
currPhase = phaseIdx.map(@(idx)phases(idx));
currOri = oriIdx.map(@(idx)oris(idx));
% create a signal to indicate the current orientation (an indicator vector)
oriMask = oris' == currOri;
% Record the last few orientations presented (buffer last few oriMasks)
oriHistory = oriMask.buffer(winlen);
% After each keypress, add the oriHistory snapshot to an accumulating
% histogram
histogram = oriHistory.at(reports).scan(@plus, zeros(numel(oris), winlen));
% Plot histogram surface each time it changes
histogram.onValue(@(data)imagesc(oris, 1:winlen, flipud(data'),...
  'Parent', axh));
```

Finally, we create the visual stimulus and send it to the renderer:

```
% Create a Gabor with changing orientations and phases
grating = vis.grating(t, 'sinusoid', 'gaussian');
grating.show = true;
grating.orientation = currOri;
grating.phase = currPhase;
grating.spatialFreq = 0.2; % cyc/deg
% Add the grating to the renderer
setElemsFun(struct('grating', grating));
```

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The Signals network representation of this experiment is shown in Figure 6.

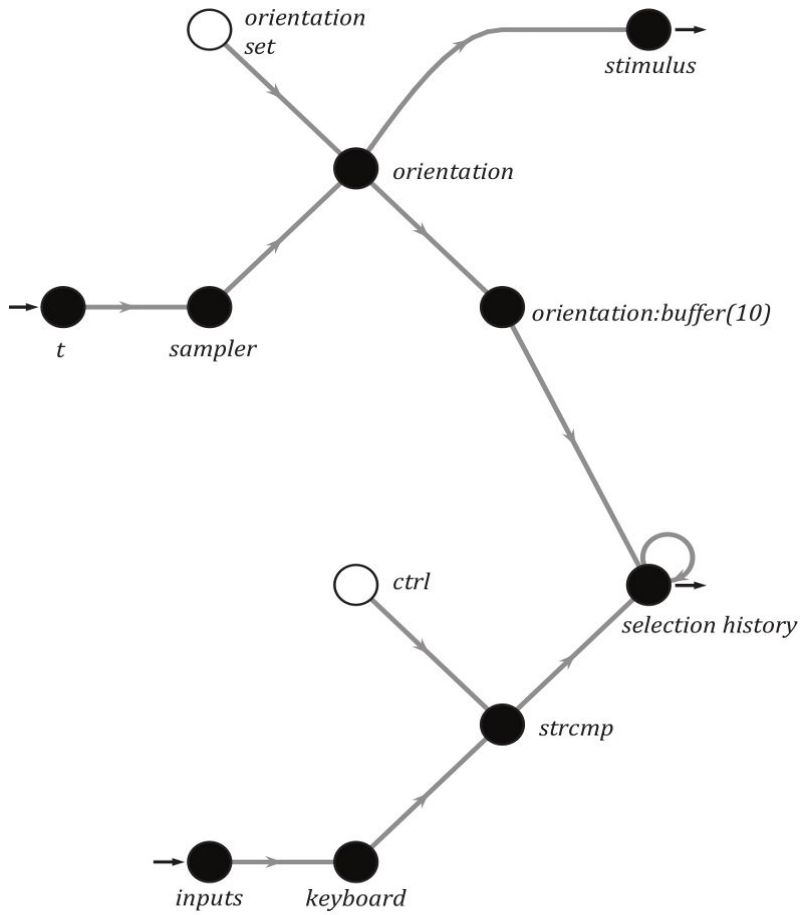

Figure 6. A simplified Signals network diagram of the Ringach experiment.

Example 2: Pong

A second human-interactive Signals experiment contained in the Rigbox repository is an exp def which runs the classic computer game, Pong (Figure 7). The signal which sets the player's paddle position is mapped to the optical mouse. The epoch structure is set so that a trial ends on a score, and the experiment ends when either the player or cpu reaches a target score.

The code is divided into three sections: 1) initializing the game, 2) updating the game, 3) creating visual elements and defining exp def parameters. To run this exp def, follow the directions in the header of the `signals/docs/examples/signalsPong.m` file in the Rigbox repository. Because the file itself (including copious documentation) is over 300 lines, we

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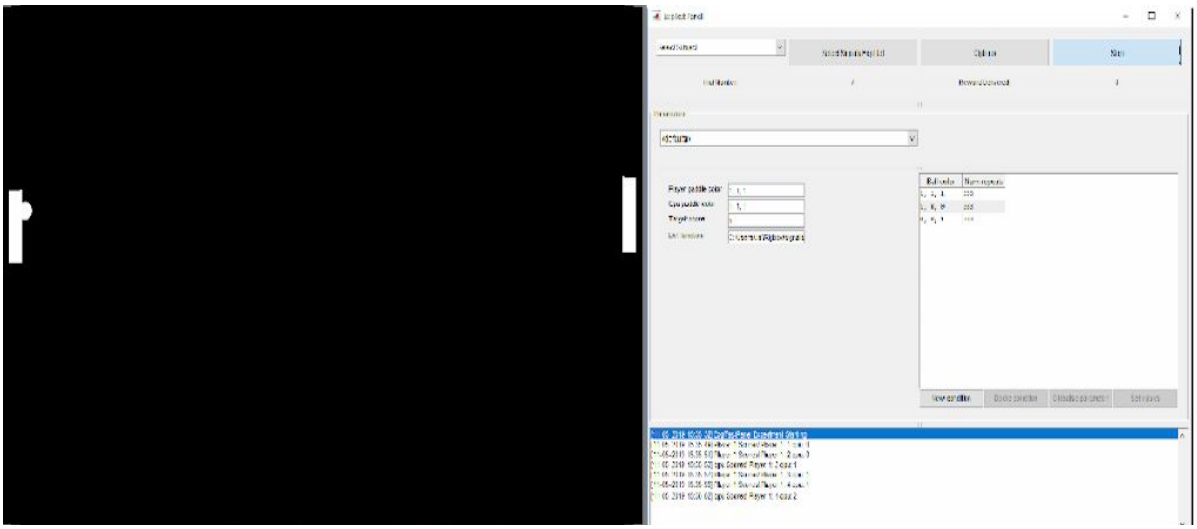

Figure 7. A screenshot of Pong run in Signals

will share only an overview here; however, readers are encouraged to look through the full file at their leisure.

```
function signalsPong(t, events, p, visStim, inputs, outputs, audio
```

In this first section, we define constants for the game, arena, ball, and paddles:

```
%% Initialize the game
% how often to update the game in secs
...
% initial scores and target score
...
% size of arena, ball, and paddle: [w h] in visual degrees
...
% ball angle, and ball velocity in visual degrees per second
...
% cpu and player paddle X axis positions in visual degrees
...
```

The helper function, “getYPos”, returns the y-position of the cursor, which will be used to set the player paddle.

```
  function yPos = getYPos()
    ...
```

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```
  end
% get cursor's initial y-position
cursorInitialY = events.expStart.map(@(~) getYPos);
```

In the second section, we define how the ball and paddle interactions update the game:

```
%% Update game
% create a signal that will update the y-position of the player's paddle
using ‘getYPos’
playerPaddleYUpdateVal = (cursor.map(@(~)getYPos)-cursorInitialY)*cursorGain
% make sure the y-value of the player's paddle is within the screen bounds,
playerPaddleBounds = cond(playerPaddleYUpdateVal > arenaSz(2)/2, ...
  arenaSz(2)/2, playerPaddleYUpdateVal < -arenaSz(2)/2, -arenaSz(2)/2, ...
  true,playerPaddleYUpdateVal);
% and only updates every 'tUpdate' secs
playerPaddleY = playerPaddleBounds.at(tUpdate);
% Create a struct, 'gameDataInit', holding the initial game state
gameDataInit = struct;
…
% Create a subscriptable signal, 'gameData', whose fields represent the
% evolving game state, and which will be updated every ‘tUpdate’ secs
gameData = playerPaddleY.scan(@updateGame, gameDataInit).subscriptable;
```

The helper function, updateGame, updates “gameData”. Specifically, it updates the ball angle, velocity, position, cpu paddle position, and player and cpu scores, based on the current ball position.

```
  function gameData = updateGame(gameData, playerPaddleY)
    ...
  end
% define trial end (when a score occurs)
anyScored = playerScore | cpuScore;
events.endTrial = anyScored.then(true);
% define game end (when player or cpu score reaches target score)
endGame = (playerScore == targetScore) | (cpuScore == targetScore);
events.expStop = endGame.then(true);
...
```

In the final section, we create the visual elements representing the arena, ball, and

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paddles, and define the exp def parameters.

```
%% Define the visual elements and the experiment parameters
% create the arena, ball, and paddles as ‘vis.patch' subscriptable signals
arena = vis.patch(t, 'rectangle');
ball = vis.patch(t, 'circle');
playerPaddle = vis.patch(t, 'rectangle');
cpuPaddle = vis.patch(t, 'rectangle');
% assign the arena, ball, and paddles to the 'visStim' subscriptable signal
handler
visStim.arena = arena;
visStim.ball = ball;
visStim.playerPaddle = playerPaddle;
visStim.cpuPaddle = cpuPaddle;
% define parameters that will be displayed in the GUI
try
  % ‘ballColor’ as conditional parameter: on any given trial, the ball color
will be
  chosen at random among three colors: white, red, blue
  p.ballColor = [1 1 1; 1 0 0; 0 0 1]’; % RGB color vector array
  p.targetScore = 5;
catch
end
```

The Other Packages in Rigbox

Often experiments are iterative: parameters are added or modified many times over and testing can be an arduous process. Rigbox allows the experimenter to develop and test their experiment without having to worry about boilerplate code and UI modifications, as these are handled by other packages in a modular fashion. Much of the code is object-oriented with most aspects of the system represented as configurable objects. Below is a short description of each package.

The **hardware package** *+hw* contains calibration functions and classes for interfacing with various hardware. These include abstract classes such as `Window` and `DaqController`, which define general methods and properties for high-level interaction with a stimulus window and a data acquisition device. These also have concrete implementations for specific systems, in this case the Psychophysics Toolbox stimulus windows and National Instruments DAQ boards. For novel implementations, these can

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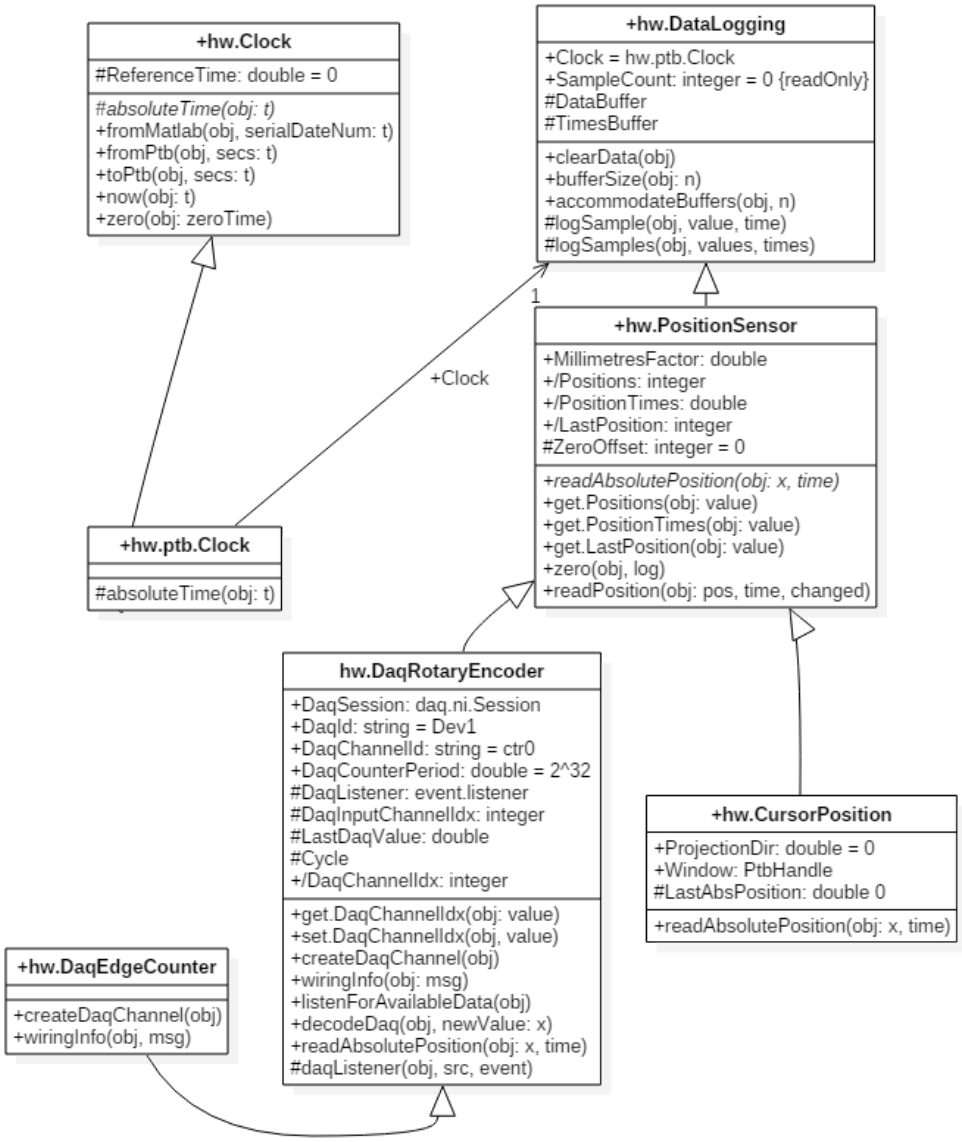

Figure 8. A UML diagram depicting the class structure for data logging in Rigbox. Each box represents a class and contained within it is the name, attributes and methods. The superclass is `DataLogging`, which contains the most general attributes and methods. `PositionSensor`, it's immediate subclass (indicated by the white arrow) provides general abstract methods such as `readAbsolutePosition` for reading the raw position of some nondescript linear position sensor. The implementation of this depends on the specific drivers and hardware of each device. Two such subclasses are shown: one for interfacing with a rotary encoder via a DAQ, and another for reading cursor position. The specific details of this need only be known to each subclass, and therefore it is straightforward to swap in different devices without having to modify other parts of the system. Also shown is the abstract `Clock` class and its concrete implementation using the Psychophysics Toolbox. The clock object is used in numerous different hardware classes and ensure that all run via the same clock.

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be subclassed with more specific hardware. For instance, the `DataLogging` class is subclassed by the `PositionSensor` class, which in turn is subclassed by `DaqRotaryEncoder` (Figure 8).

The hardware package also contains a class called `Timeline` which manages the acquisition and generation of experimental timing data using a NI-DAQ. The main timing signal, "chrono", is a digital square wave that flips each time a new chunk of data is available from the DAQ. A callback function to this flip event collects the DAQ timestamp of the scan where each flip occured. The difference between this timestamp and the system time recorded when the flip command was given is recorded as the "offset time" and can be used to unify all timestamps across computers during an experiment. Thus, all event timestamps across all computers for a given experiment are recorded in times relative to "chrono". Timeline can acquire any number of hardware events and record their values with respect to this offset; for example, Timeline can use a photodiode to record the times at which the screen updates.

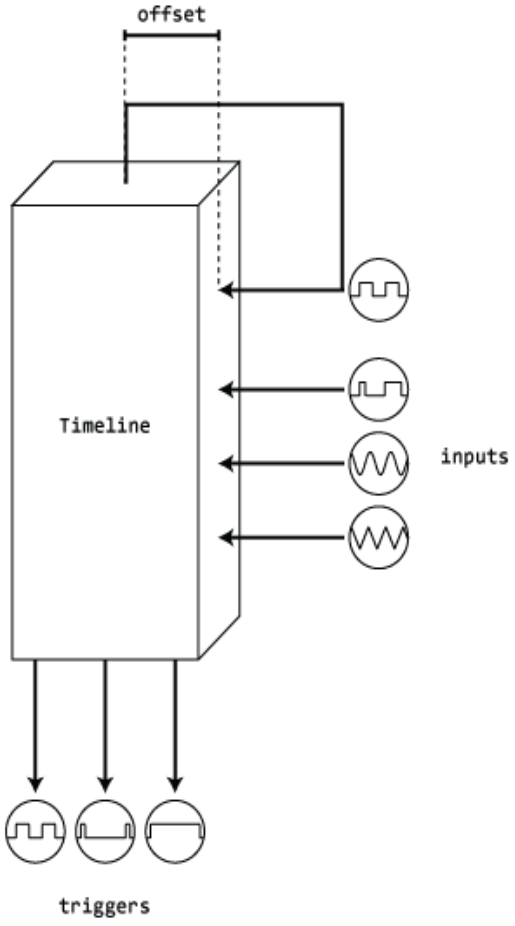

Figure 9. Representation of a Timeline object. The top most signal is the main timing signal, "chrono", which is used to unify all timestamps across computers during an experiment. The "inputs" represent different hardware input signals read by a DAQ, and the "triggers" represent different hardware output signals, triggered by a DAQ.

In addition to chrono, Timeline can also output TTL and clock pulses for triggering external devices (e.g. to acquire frames at a specific rate).

The **data package** *+dat* contains a number of simple functions for saving and locating data. Data organization supports separation of data types between repositories, and redundant local and remote storage. Because all code uses the same paths file, it is very simple to change the location of data and

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configuration files. Furthermore, this system can be easily used with one's own code to generate read and write paths for arbitrary datasets.

The **experiment package** *+exp* contains all of the code pertaining to experiment setup and configuration. Two key aspects of this are the `Parameters` class, which sets, validates, and assorts experiment conditions for each experiment, and the `SignalsExp` class, which runs an experiment after loading in the experimenter's exp def and appropriate parameters into a Signals network.

The **server package** *+srv* provides high level network communication between MC and SC. In addition, this package provides functions for triggering remote recording software via UDPs.

The **experiment UI package** *+eui* provides all the graphical user interface (GUI) code. Principally, this is employed for the `mc` function, which builds the main GUI on MC. The MC GUI is used to load and configure experiment parameters on MC, monitor experiments through customizable plots, view experiment history, and log metadata.

The **psychometrics package** *+psy* contains simple functions for processing and plotting psychometric data.

The **alyx-matlab** package serves as a MATLAB client for interfacing with an Alyx database. This package allows experimenters to make notes during an experiment which are automatically synced to the Alyx database, and uses the NPY-MATLAB submodule to provide support for saving data.

Alyx is a meta-database that allows experimenters to keep track of animal procedures, such as breeding and implantation, and organize experimental sessions and their associated files (Rossant et. al, 2018). The database is heavily used by the International Brain Laboratory due to its lightweight nature, and can be easily installed on most web servers (Abbott et al., 2017). More information on Alyx and alyx-matlab can be found in `alyx-matlab\docs` within the Rigbox repository. The use of Alyx and alyx-matlab within Rigbox is optional.

Benchmarking

Fast execution of experiment runtime code is crucial for performing and accurately analyzing results from a behavioral experiment. Here we show benchmarking results for the Signals framework. We include results for individual operations on a signal, and for operations which propagate through each signal in a network. Single built-in MATLAB

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operations and Signals-specific methods are consistently executed in the microsecond range (Figure 10a). The largest network we benchmark contains 1,000 signals spread over 20 layers. This network is able to update all of its signals in under 15 milliseconds (Figure 10b). (*Note, this is a very large network: for comparison, the network used in the version of the Burgess Steering Wheel Task implemented in `signals/docs/examples/advancedChoiceWorld.m` has 338 nodes spread over 10 layers (Burgess et al. 2017)). Lastly, we include results from running the Burgess Steering Wheel Task in Signals. Updates of the wheel position typically took less than 2 milliseconds; the time between rendering and displaying the visual stimulus typically took less than 15 milliseconds; the delay between triggering and delivering a reward was typically under 0.2 milliseconds (Figure 11).

All results in the Benchmarking section were obtained from running MATLAB 2018b on a Windows 10 64-bit OS with an Intel core i7 8700 processor and 16 GB DDR4 dual channel RAM clocking at 1067 MHz (2133 MHz with DDR). Because single executions of signals operations were too quick for MATLAB to measure accurately, we repeated operations 1,000 times. Thus, when calculating the measured time of a single operation, we divided MATLAB's returned measured time by 1,000. MATLAB 2018b's Performance Testing Framework was used to obtain the results in Figure 7a-c. The code used to generate these results can be found in the `signals/tests/Signals_perftest.m` file. A complete table of these results can be found in the `signals/tests/results/2019-06-14_Signals_perftest.mat` file. The results shown in Figure 7d can be obtained from the `signals/tests/results/2019-06-04_advancedChoiceWorld_Block.mat` file - the data in this file was saved at the end of the experiment. The data acquisition device used was National Instrument's USB-6211.

DISCUSSION

In our laboratory, Rigbox is at the core of our operant, passive, and conditioning experiments. The principal behavioral task we use is the Burgess Steering Wheel Task - a two alternative choice task involving manipulation of a wheel by a mouse to report detection of a visual stimulus for a water reward (Burgess et al., 2017). Using Rigbox, we have been able to create multiple variants of this task. These include unforced choice, multisensory choice, behavior matching, and bandit tasks, using wheels, levers, balls, and lick detectors.

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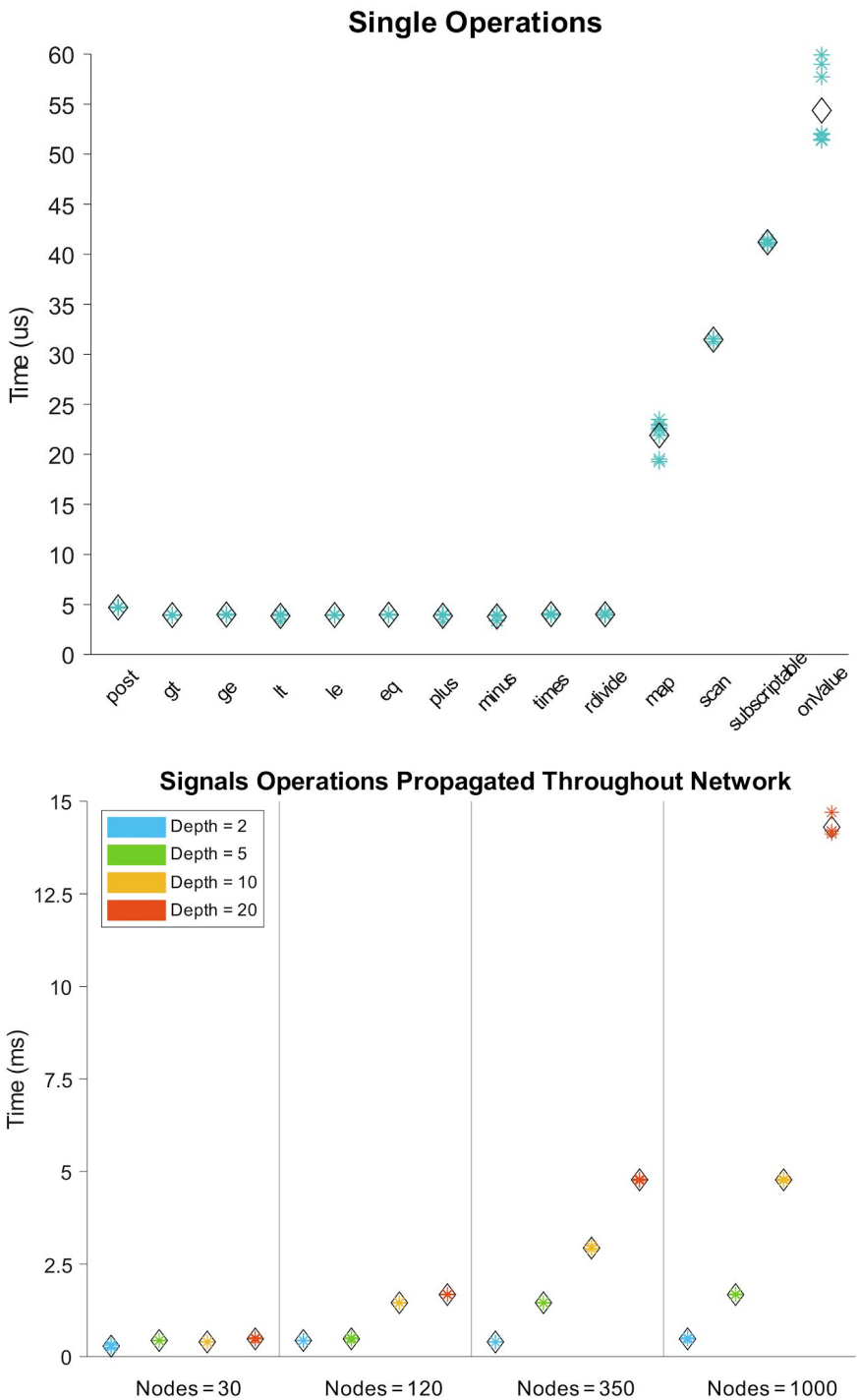

Figure 10: Benchmarking results for operations on a single signal (**a**), and for updating an entire network of signals (**b**). Panel **a)** shows the times for performing an operation on a single signal, for various operations. Panel **b)** shows the times for updating every signal in a network, for networks of various size (number of nodes) and depth (number of layers). The number of samples run for each group was determined by MATLAB's performance testing framework. The black diamond shows the mean value per group.

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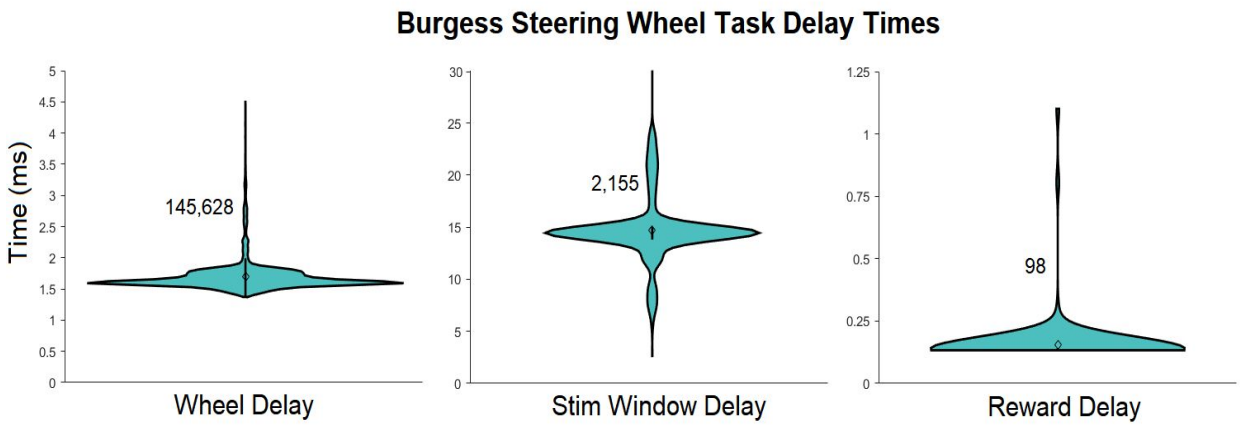

Figure 11: Violin plots of the delay times for specific updates when running the version of the Burgess Steering Wheel Task implemented in `signals/docs/examples/advancedChoiceWorld` exp def. The number to the left of each violin plot represents the number of samples in the group. "Wheel Delay" is the time between polling consecutive position values from the hardware wheel. "Stim Window Delay" is the time between triggering a display to be rendered, and it's complete render on a screen. "Reward Delay" is the time between triggering a reward to be delivered and its delivery. (*Note, 99th percentile outliers were not included in the plot for "Wheel Delay". There were 98 instances in which the wheel delay took between 200-600 ms: these long delay times are due to execution time of the NI-DAQmx MATLAB package when sending analog output (reward delivery) via the USB-6211 DAQ).

In addition, Rigbox has allowed us to rapidly integrate these tasks with a variety of recording techniques, including electrode recordings, 2-Photon imaging, and fiber photometry, and neural perturbations such as scanning laser inactivation and dopaminergic stimulation (Jun et al., 2017; Jacobs et al., 2018; Lak et al., 2018; Steinmetz et al., 2018; Shimaoka et al., 2018; Zatka-Haas et al., 2018).

Given the modular nature of Rigbox, new features and hardware support may be easily added, provided there is driver support in MATLAB. For example, to add support for a novel data acquisition device (such as an Arduino or other microcontroller), one can simply create a subclass of the `+hw/DaqController` class. Similarly, to add support for a novel position sensor, a new `+hw/PositionSensor` subclass could be created. These classes simply define what happens when, for example, the code triggers a hardware output, or polls a hardware input. This principle also holds true for implementing various visual stimulus viewing models, of which there is currently only one. A new viewing model class could be implemented to allow for virtual reality experiments, for example.

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	BControl	**Bpod**	**pyControl**	**VirMEn**	**Rigbox**
Behavioral task design paradigm	Procedural	Procedural	Procedural	Object-Oriented	Functional Reactive
Implements viewing model? 3D viewing model?	no	no	no	yes, yes	yes, no
Interfaces with hardware?	yes	yes	yes	yes	yes
Synchronizes multiple datastreams?	yes	yes	yes	no	yes
Communicates with a remote database?	yes	yes	no	no	yes

Table 1: Comparison of major features across behavioral control system toolboxes. The top row contains the toolbox names, and the first column contains information on a feature's implementation. Note, the toolboxes and features mentioned in this table are not exhaustive.

To the best of our knowledge, Rigbox is the most complete behavioral control system toolbox currently available in the behavioral neuroscience community (Table 1). However, a number of other toolboxes implement similar features in different ways (Bcontrol 2014; Sanders 2019; Akam 2019; Aronov and Tank, 2014). Some of these toolboxes also include some features not currently available in Rigbox, for example, microsecond precision triggering of within-trial events and creating 3D virtual environments. Indeed, the features employed by a particular toolbox have advantages (and disadvantages) depending on the user's desired experiment.

For software developers deciding how an experimenter is to programatically design a behavioral task, there are pros and cons to following different programming paradigms. Generally, three main paradigms have emerged: procedural, object-oriented, and functional reactive. Here, in the context of programmatic task design, we briefly discuss the differences between these paradigms, and in which scenarios one may be favored over the others. Note that these paradigms exist generally in software development, across various fields and contexts. Also note that here we only discuss the aspect of the toolbox that deals with behavioral task design, not the overall structure of the toolbox - e.g. Rigbox is built on an object-oriented paradigm, but Signals provides a functional reactive paradigm in which to implement a behavioral task.

A procedural approach to task design is probably the most familiar to behavioral

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neuroscientists. This approach focuses on "how to execute" a task by explicitly defining a control flow that moves a task from one state to the next. The Bcontrol, Bpod, and pyControl toolboxes follow this paradigm by using a real-time finite state machine (RTFSM) which controls a task's state (e.g. initial state, reward, punishment, etc…) during each trial. Some advantages of this approach are that it's simple and intuitive, and guarantees event timing precision down to the minimum cycle of the state machine (e.g. Bcontrol RTFSMs run at a minimum cycle of 6 KHz). Some disadvantages of this approach are that the memory for task parameters are limited by the RTFSM's number of states, and that the discrete implementation of states isn't amenable to experiments which seek to control parameters continuously (e.g. a task which uses continuous hardware input signals).

Like the procedural approach to task design, an object-oriented approach also tends to be intuitive: objects can neatly represent an experiment's state via datafields. Objects representing experimental parameters can easily pass information to each other, and trigger experimental states via event callbacks. The VirMEn toolbox implements this approach by treating everything in the virtual environment as an object, and having a runtime function update the environment by performing method calls on the objects based on input sensor signals from a subject performing a task. Some disadvantages of this approach are that the speed of experimental parameter updates are limited by the speed at which the programming language performs dynamic binding (which is often much slower than the RTFSM approach discussed above), and that operation "side effects" (which can alter an experiment's state in unintended ways) are more likely to occur due to the emphasis on mutability, when compared to a pure procedural or functional reactive approach.

By contrast, Signals follows a functional reactive approach to task design. As we have seen, some advantages of this approach include simplifying the process of updating experimental parameters over time, endowing parameters with memory, and facilitating discrete and continuous event updates with equal ease. In general, a task specification in this paradigm is declarative, which can often make it clearer and more concise than in other paradigms, where control flow and event handling code can obscure the semantics of the task. Some disadvantages are that it suffers from similar speed limitations as in an object-oriented approach, and programmatically designing a task in a functional reactive paradigm is probably unfamiliar to most behavioral neuroscientists. When considering the entire set of behavioral tasks, no single programming paradigm is perfect, and it is therefore important for an experimenter to consider the goals for their task's implementation accordingly.

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Rigbox is currently under active, test-driven development. All our code is open source, distributed under the Apache 2.0 license, and we encourage users to contribute. Please see the contributing guidelines in the repository for contributing code and reporting issues.

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REFERENCES

Abbott, L. F., Angelaki, D. E., Carandini, M., Churchland, A. K., Dan, Y., Dayan, P., … Zador, A. M. (2017). An International Laboratory for Systems and Computational Neuroscience. *Neuron*, *96*(6), 1213–1218.

Akam, T. pyControl. (2019). Retrieved June 7, 2019, from https://pycontrol.readthedocs.io/en/latest/

Aronov, D. and Tank, D. W. (2014) Engagement of Neural Circuits Underlying 2D Spatial Navigation in a Rodent Virtual Reality System. *Neuron 84*(2): 442-56.

Bcontrol. (2014). Retrieved May 11, 2019, from https://brodywiki.princeton.edu/bcontrol/index.php?title=Main_Page

Burgess, C. P., Lak, A., Steinmetz, N., Zatka-Haas, P., Bai Reddy, C., Jacobs, E. A. K., … Carandini, M. (2017). High-yield methods for accurate two-alternative visual psychophysics in head-fixed mice. *Cell Reports*, *20*(10), 2513-2524.

Carandini, M., and Churchland, A.K. (2013). Probing perceptual decisions in rodents. *Nat Neurosci 16*, 824-831.

Jacobs, E. A. K., Steinmetz, N. A., Carandini, M., & Harris, K. D. (2018). Cortical state fluctuations during sensory decision making. *BioRxiv*, 348193.

Jun, J. J., Steinmetz, N. A., Siegle, J. H., Denman, D. J., Bauza, M., Barbarits, B., … Harris, T. D. (2017). Fully integrated silicon probes for high-density recording of neural activity.

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Nature, *551*(7679), 232–236.

Lak, A., Okun, M., Moss, M., Gurnani, H., Wells, M. J., Reddy, C. B., … Carandini, M. (2018). Dopaminergic and frontal signals for decisions guided by sensory evidence and reward value. *BioRxiv*, 411413.

Lew, D. An Introduction to Functional Reactive Programming. (2017). Retrieved May 23, 2019, from Dan Lew Codes website: https://blog.danlew.net/2017/07/27/an-introduction-to-functional-reactive-programming/

Lee D., Conroy M.L., McGreevy B.P., Barraclough D.J. (2004) Reinforcement learning and decision making in monkeys during a competitive game. *Cog Brain Res 22*(1)

Ringach, D.L. (1998). Tuning of orientation detectors in human vision. *Vision Res 38*, 963-972.

Rossant, C., Hunter, M., Winter, O., Burgess, C., Harris, K. Alyx (2018). Retrieved May 23, 2019, from https://alyx.readthedocs.io/en/latest/

Sanders, J. Bpod Wiki. (2019). Retrieved May 11, 2019, from https://sites.google.com/site/bpoddocumentation/home

Shimaoka, D., Steinmetz, N. A., Harris, K. D., & Carandini, M. (2018). The impact of bilateral ongoing activity on evoked responses in mouse cortex. *BioRxiv*, 476333.

Steinmetz, N. A., Zatka-Haas, P., Carandini, M., & Harris, K. D. (2018). Distributed correlates of visually-guided behavior across the mouse brain. *BioRxiv*, 474437.

Zatka-Haas, P., Steinmetz, N. A., Carandini, M. Harris, K.D. (2018). Distinct contributions of mouse cortical areas to visual discrimination. *BioRxiv*, 501627