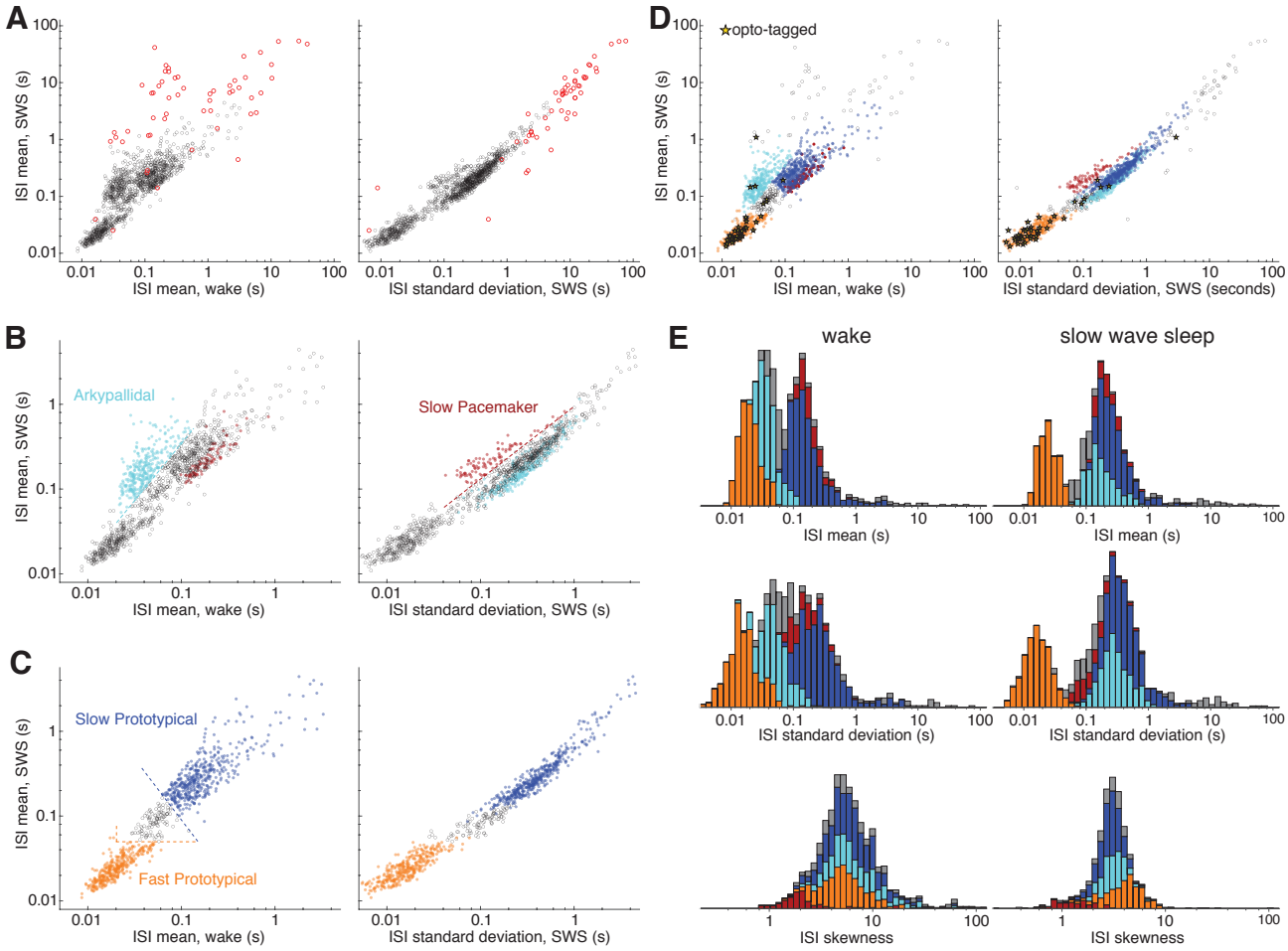
A
ISI mean, SWS (s)
ISI mean, wake (s)
ISI standard deviation, SWS (s)
D
opto-tagged
ISI mean, SWS (s)
ISI mean, wake (s)
ISI standard deviation, SWS (seconds)
B
Arkypallidal
Slow Pacemaker
ISI mean, SWS (s)
ISI mean, wake (s)
ISI standard deviation, SWS (s)
C
Slow Prototypical
Fast Prototypical
ISI mean, SWS (s)
ISI mean, wake (s)
ISI standard deviation, SWS (s)
E
wake
slow wave sleep
ISI mean (s)
ISI standard deviation (s)
ISI skewness

Figure S1. Classification of GPe neurons. Related to Figure 1.

A-C indicate the steps in our classification procedure.

(A) ISI mean during SWS for each cell plotted as a function of ISI mean during wakefulness (*left*) and ISI standard deviation during SWS (*right*). *Red circles*, cells whose ISI statistics were considered outliers (see Methods); these cells were not included in the main classification into 4 cell types. A subset of these outlier cells may be cholinergic neurons as they greatly reduce firing during SWS (see Figure S6).

(B) Classification of cells deviating from the prototypical ISI relationship governing most GPe cells. Same data as *A*, but with the outliers omitted. *Left*, Arkys are defined as cells whose SWS ISI mean lies above the SWS ISI mean – wake ISI mean relationship shown here (*light blue dashed line*) while having a wake ISI mean of 20 – 135 ms. *Right*, Slow Pacemakers are defined as cells whose SWS ISI mean lies above the SWS ISI mean – SD relationship shown here (*dark red dashed line*) while having a SWS ISI SD of 0.04 – 1.0 s.

(C) Classification of Prototypical GPe cells. Same data as *B*, but with Arkys and Slow Pacemakers omitted. The cells plotted here illustrate the "Prototypical" relationship among GPe cells between SWS ISI mean, SWS ISI SD, and wake ISI mean. Fast Protos are defined as Prototypical pallidal cells with a SWS ISI mean < 50 ms or a wake ISI mean < 20 ms (*orange dashed lines*). Slow Protos are defined as cells whose SWS ISI mean lies above the SWS ISI mean – wake ISI mean relationship shown here (*blue dashed line*).

(D) Same as *A*, but with cell classification indicated by fill color. *Yellow stars* denote opto-tagged cells recorded in PV-Cre rats. *Open circles* denote unclassified cells.

(E) Distributions of the first 3 central moments of the ISIs of GPe cells during wakefulness and slow wave sleep. Colors of stacked bars show the cells in each histogram bin belonging to each cell type. Strictly speaking, the 2nd row (standard deviation) is the square root of the second central moment, the variance. The ISI means and the ISI SD during SWS are manifestly bimodal. For ISI mean and SD during SWS, one peak is dominated by fast Protos while all other cell types fall into the second peak. Skewness (3rd row) is unimodal in wakefulness and SWS, but the slow pacemakers are concentrated in the low-skew tail in both states.

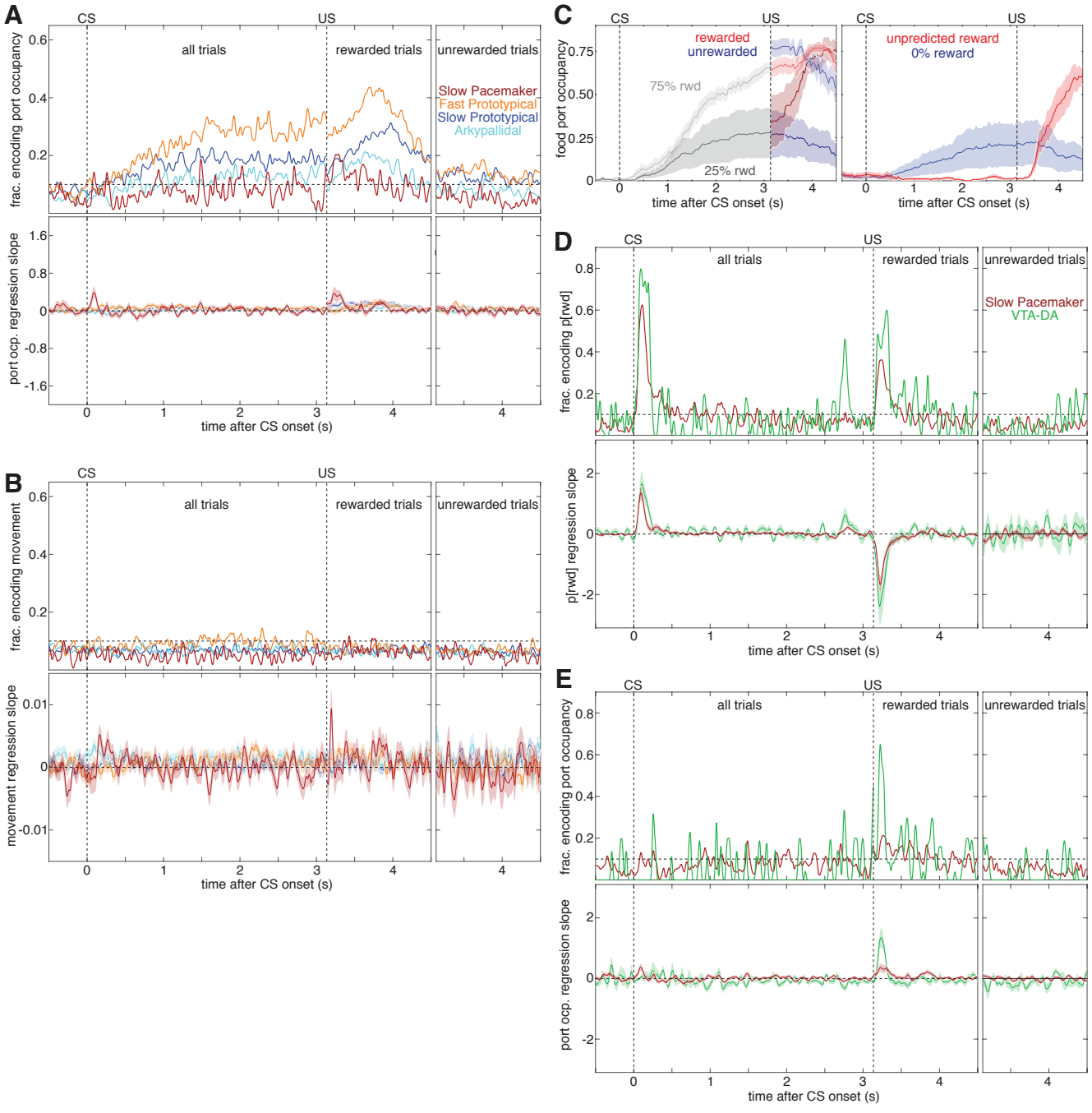
A
CS
US
all trials
rewarded trials
unrewarded trials
frac. encoding port occupancy
Slow Pacemaker
Fast Prototypical
Slow Prototypical
Arkypallidal
port ocp. regression slope
time after CS onset (s)
B
frac. encoding movement
movement regression slope
time after CS onset (s)
C
rewarded
unrewarded
75% rwd
25% rwd
food port occupancy
time after CS onset (s)
unpredicted reward
0% reward
time after CS onset (s)
D
frac. encoding p[rwd]
Slow Pacemaker
VTA-DA
p[rwd] regression slope
time after CS onset (s)
E
frac. encoding port occupancy
port ocp. regression slope
time after CS onset (s)

Figure S2. Behavioral correlates during Pavlovian conditioning. Related to Figure 2.

(A) Coding of food port occupancy in the Pavlovian task, from the same regression model featured in Figure 2B, C. *Top*, fraction of cells in each GPe cell type encoding food port occupancy as a function of time in trial. *Bottom*, mean regression slope for food port occupancy for each cell type. *Shaded areas* show SE.

(B) Coding of movement in the Pavlovian task measured from accelerometer signals. This regressor was included in the regression model featured in Figure 2B, C. *Top*, fraction of cells in each GPe cell type encoding movement as a function of time in trial. *Bottom*, mean regression slope for movement for each cell type. *Shaded areas* show SE.

(C) Average behavior in the Pavlovian task during recordings of VTA DA neurons. *Solid lines* plot mean, *shaded areas* show SE. Same format as Figure 2A.

(D) Comparison of value coding in the Pavlovian task in GPe Slow Pacemakers (*dark red*) and VTA DA cells (*green*). Because VTA recordings lacked accelerometer data, movement was not included in this regression model. Slow Pacemaker results based on the same data as Figure 2B-C, but the regression model here excludes movement to allow a direct comparison to VTA data. *Top*, fraction of cells encoding cued reward probability as a function of time in trial. *Bottom*, mean regression slope for cued reward probability. *Shaded areas* show SE.

(E) Comparison of coding of food port occupancy between GPe Slow Pacemakers and VTA DA cells (same regression model as *D*). *Top*, fraction of cells encoding food port occupancy as a function of time in trial. *Bottom*, mean regression slope for food port occupancy. *Shaded areas* show SE.

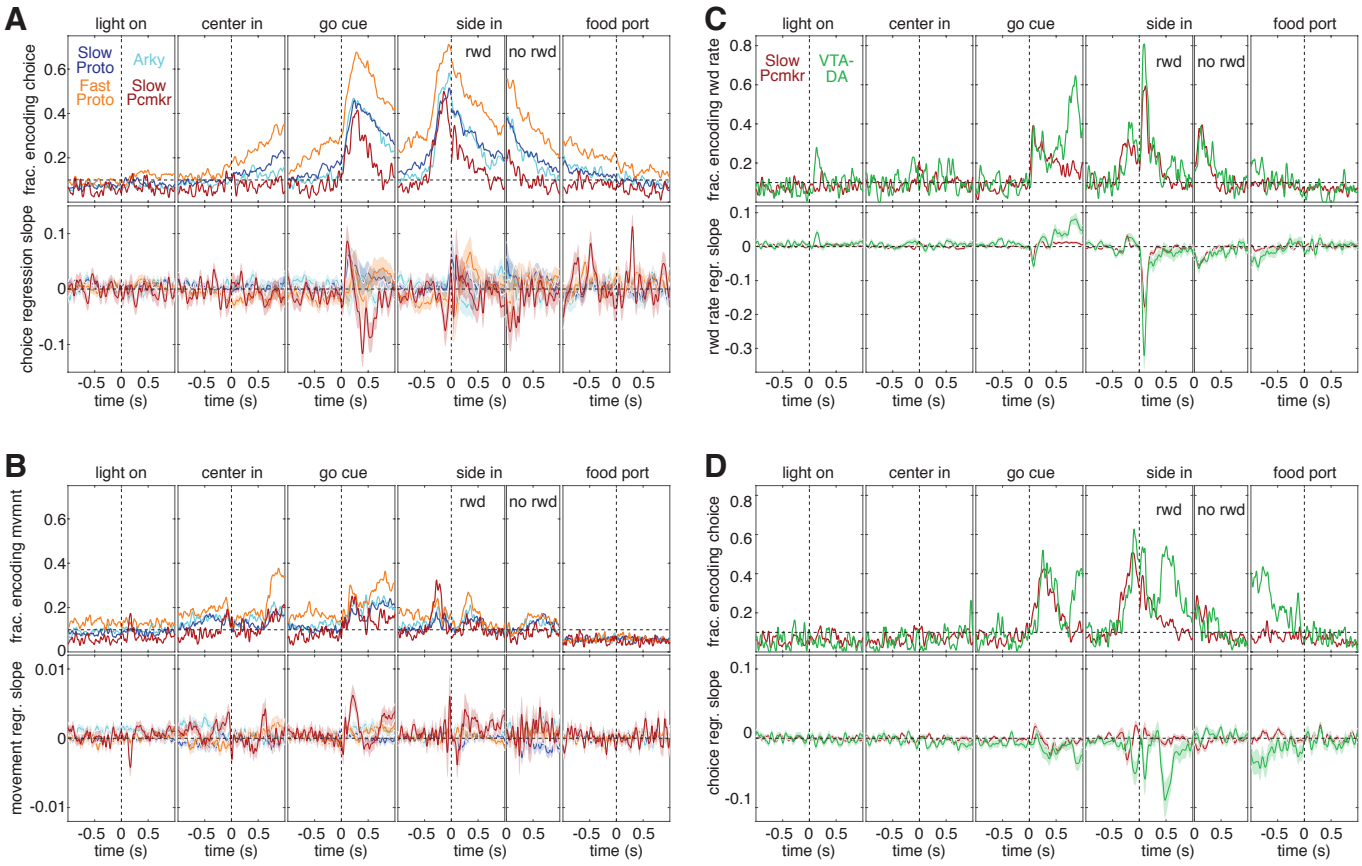
A
light on
center in
go cue
side in
food port
rwd
no rwd
Slow Proto
Arky
Fast Proto
Slow Pcmkr
frac. encoding choice
choice regression slope
time (s)
C
Slow Pcmkr
VTA-DA
frac. encoding rwd rate
rwd rate regr. slope
B
frac. encoding mvmnt
movement regr. slope
D
frac. encoding choice
choice regr. slope

Figure S3. Behavioral correlates during instrumental learning. Related to Figure 3.

(A) Coding of choice (left or right nosepoke port) in the instrumental task, from the same regression model featured in Figure 3F. *Top*, fraction of cells in each GPe cell type encoding choice as a function of time in trial. *Bottom*, mean regression slope for choice for each cell type. *Shaded areas* show SE.

(B) Coding of movement in the instrumental task measured from accelerometer signals. This regressor was included in regression model featured in Figure 3F. *Top*, fraction of cells in each GPe cell type encoding movement as a function of time in trial. *Bottom*, mean regression slope for movement for each cell type. *Shaded areas* show SE.

(C) Comparison of value coding in the instrumental task in GPe Slow Pacemakers (*dark red*) and VTA DA cells (*green*). Because VTA recordings lacked accelerometer data, movement was not included in this regression model. Slow pacemaker results based on the same data as Figure 3F, but the regression model here excludes movement to allow a direct comparison to VTA data. *Top*, fraction of cells encoding reward rate as a function of time in trial. *Bottom*, mean regression slope for reward rate. *Shaded areas* show SE.

(D) Comparison of coding of choice between GPe Slow Pacemakers and VTA DA cells (same regression model as *C*). *Top*, fraction of cells encoding choice as a function of time in trial. *Bottom*, mean regression slope for choice. *Shaded areas* show SE.

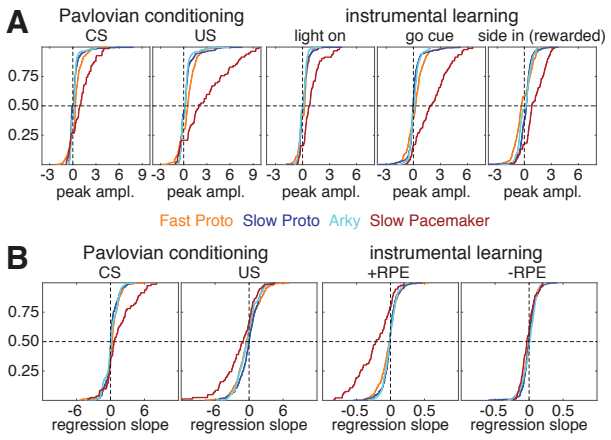
A
Pavlovian conditioning
instrumental learning
CS
US
light on
go cue
side in (rewarded)
0.75
0.50
0.25
-3 0 3 6 9
-3 0 3 6
peak ampl.
Fast Proto
Slow Proto
Arky
Slow Pacemaker
B
Pavlovian conditioning
instrumental learning
CS
US
+RPE
-RPE
-6 0 6
-0.5 0 0.5
regression slope

Figure S4. Phasic responses and value coding across GPe cell types. Related to Figure 4.

(A) Phasic responses to key events and cues in the Pavlovian and instrumental tasks across all GPe cell types. Phasic responses were measured as described for Figure 4A, save that firing rates were z-scored. Each panel plots the cumulative distributions for z-scored peak response, whether statistically significant or not, for all GPe cell types. Pavlovian CS responses (*left*) average together the responses from all 3 CS types. The distributions for Slow Pacemakers are qualitatively different from those of all other GPe cell types, and no other cell types show evidence for a substantial subpopulation that respond similarly to as Slow pacemakers.

(B) Value coding in the peak responses to value-updating events in the Pavlovian and instrumental tasks across all GPe cell types. Each panel plots the cumulative distributions of the regression slopes of value against peak z-scored firing rate changes, regardless of statistical significance. The distributions for slow pacemakers are qualitatively different from those of all other GPe cell types save for cases where reward was omitted in the instrumental task (*right*, "-RPE").

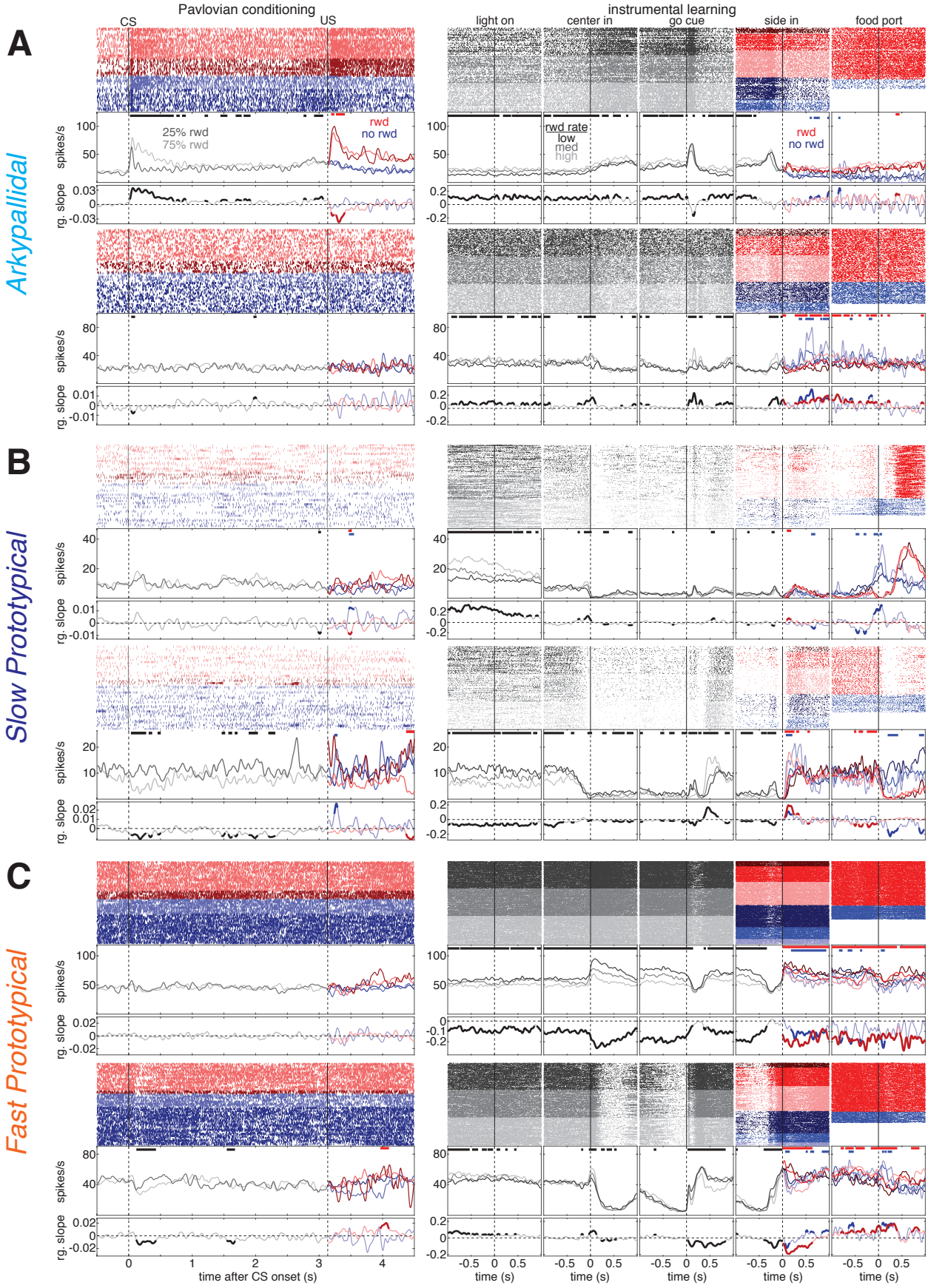
A
Arkypallidal
B
Slow Prototypical
C
Fast Prototypical
Pavlovian conditioning
CS
US
instrumental learning
light on
center in
go cue
side in
food port
spikes/s
rg. slope
25% rwd
75% rwd
rwd
no rwd
rwd rate
low
med
high
time after CS onset (s)
time (s)

Figure S5. Examples of Prototypical and Arkypallidal value-coding cells. Related to Figure 5.

(A) Two examples of Fast Protos encoding value at some point in either the Pavlovian or instrumental tasks. In each example, the *top* panels show rasters of spikes fired on each trial. The *middle* panels show average firing rate for each condition; color scheme is the same as Figures 2D and 3D. The *bottom* panels plot the corresponding regression slope for value. Here, the slope trace is plotted in as a darker, thicker line when significantly different from zero. Regions with significant regression slope are also marked at the top of firing rate plots above *(thick horizontal bars*).

(B) Two examples of Slow Protos encoding value; otherwise same as *A*.

(C) Two examples of Arkypallidal neurons encoding value; otherwise same as *A*.

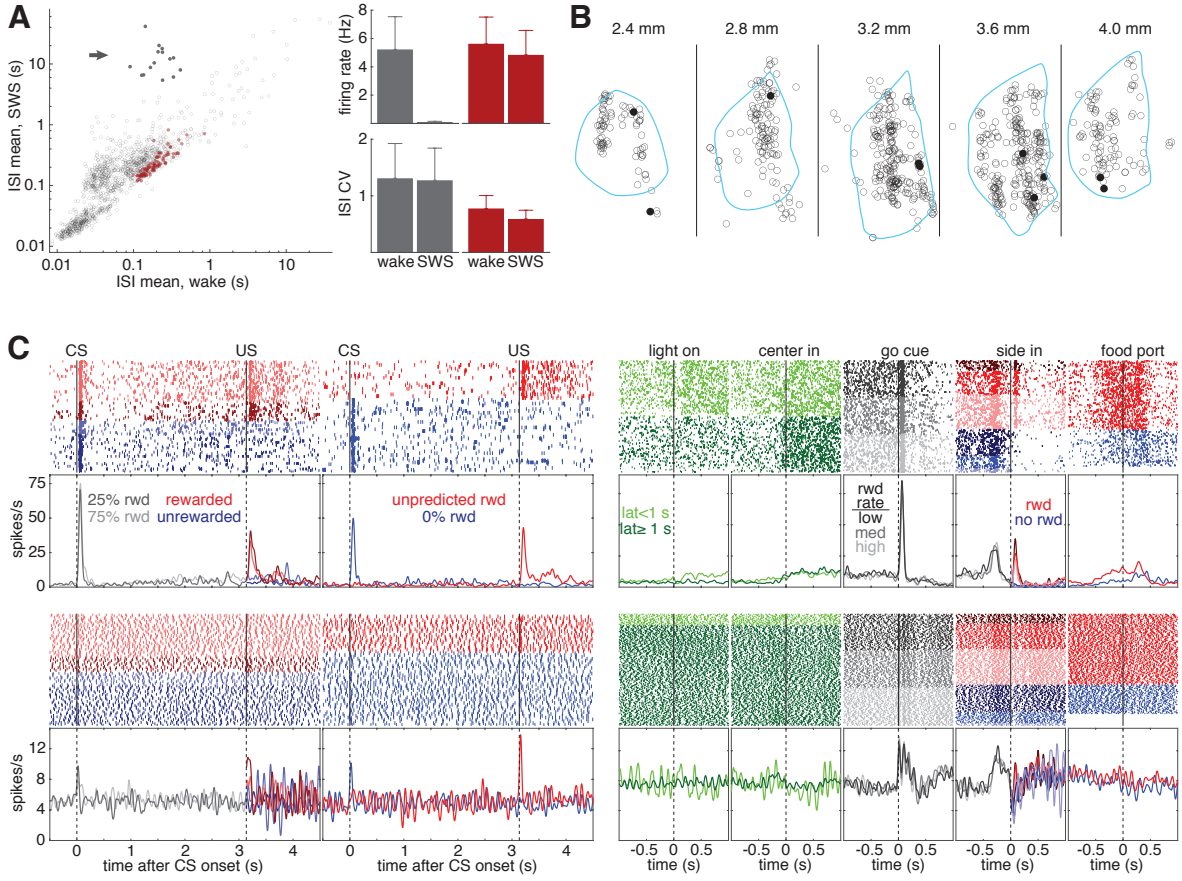
A
ISI mean, SWS (s)
ISI mean, wake (s)
0.01
0.1
1
10
firing rate (Hz)
ISI CV
wake SWS wake SWS
B
2.4 mm
2.8 mm
3.2 mm
3.6 mm
4.0 mm
C
CS
US
CS
US
spikes/s
25% rwd rewarded
75% rwd unrewarded
unpredicted rwd
0% rwd
time after CS onset (s)
light on
center in
go cue
side in
food port
lat<1 s
lat≥ 1 s
rwd rate
low
med
high
rwd
no rwd
time (s)

Figure S6. Candidate cholinergic cell type has distinct properties to Slow Pacemakers. Related to Figures 1-3, 6.

(A) *Left*, scatterplot of average ISI mean during slow wave sleep as a function of ISI mean during wakefulness for all recorded GPe cells. *Dark red circles* show the Slow Pacemakers. The *gray arrow* points to a loose cluster of 15 cells (*gray circles*) that were classified as outliers in our initial analysis (Figure S1A; see Methods). *Right*, mean firing rate and ISI CV during wakefulness and sleep for these putative cholinergic neurons (*gray*) and Slow Pacemakers (*dark red*). During wakefulness, these cells fire at rates comparable to Slow Pacemakers, but during SWS their firing rate drops dramatically while the Slow Pacemaker firing rate is only slightly reduced. These cells fire in a less regular pattern on average than do Slow Pacemakers (i.e., higher ISI CV) during both wakefulness and sleep.

(B) Locations of the 10 putative cholinergic neurons that were recorded in wildtype rats. *Open circles* show all GPe neurons, *filled circles* show the putative cholinergic neurons. See Figure 6A for details on how location information is displayed and for locations of Slow Pacemakers. Like Slow Pacemakers, the putative cholinergic cells appear more common in ventral GPe, but unlike Slow Pacemakers they tend to be confined to caudal GPe. The 2 putative cholinergic cells in the lateral-most section (*right*) appear to be relatively rostral, but this is an illusion caused by the fact that the lateral GPe curves caudally as it extends laterally. These two cells are very close to the medial boundary of this section and are actually in the caudal half of the GPe at that location; if plotted with the cells the medially adjacent section (3.6 mm ML), they would cluster with the 3 putative cholinergic cells appearing in that section.

(C) Two examples of putative cholinergic neurons recorded during both Pavlovian (*left*) and instrumental (*right*) tasks. Format follows Figures 2, 3. *Top*, example of a cell generating a response pattern resembling an RPE, at least in the instrumental task. This cell also produces phasic responses to CS and US (Pavlovian) and to the go cue (instrumental). Despite some superficial similarities to Slow Pacemakers, this cell differs from the typical Slow Pacemaker response in several ways: the Pavlovian phasic responses do not encode value, there is no phasic response to “light on” in the instrumental task, there is a response to acquisition of the sugar pellet at the food port, and the cell’s activity between phasic responses is quite bursty (e.g., the interval between CS and US). Nevertheless, of the 15 recorded putative cholinergic neurons, this cell best resembled Slow Pacemakers. *Bottom*, a more typical example of a putative cholinergic neuron exhibiting very short-latency responses to auditory cues, with resetting of firing phase (e.g., following the “go cue”).