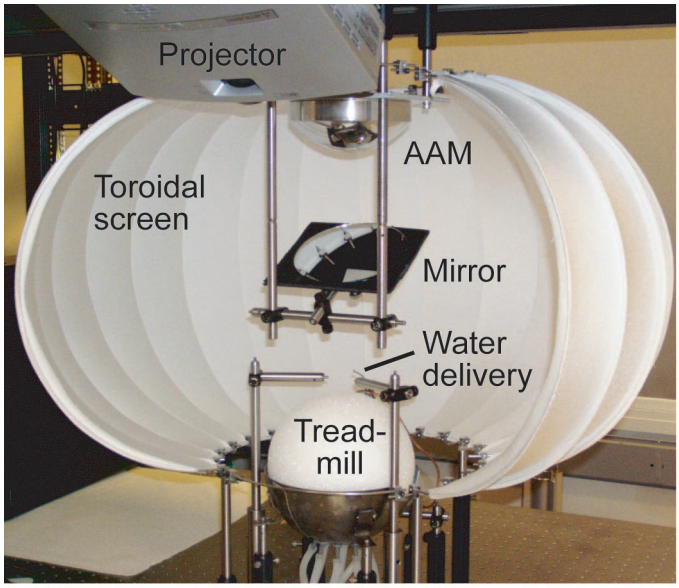
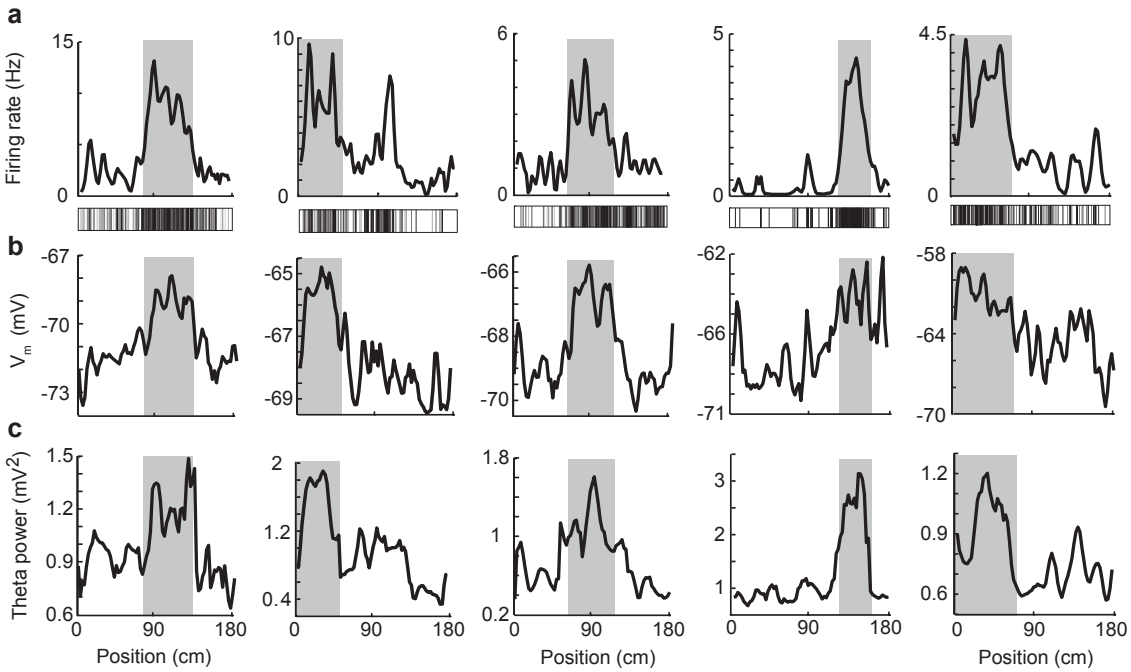
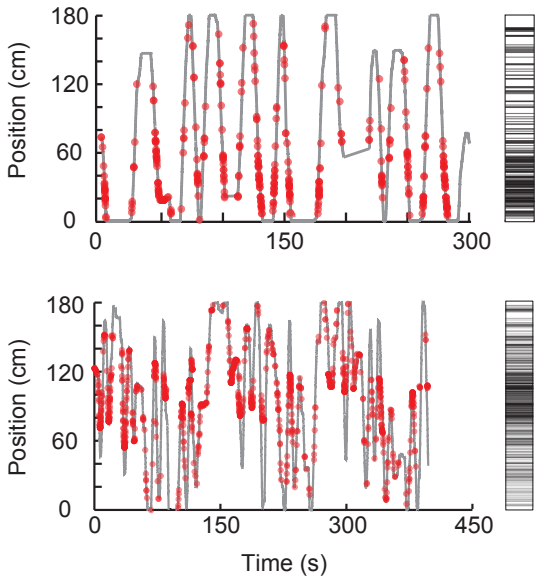
SUPPLEMENTARY INFORMATION



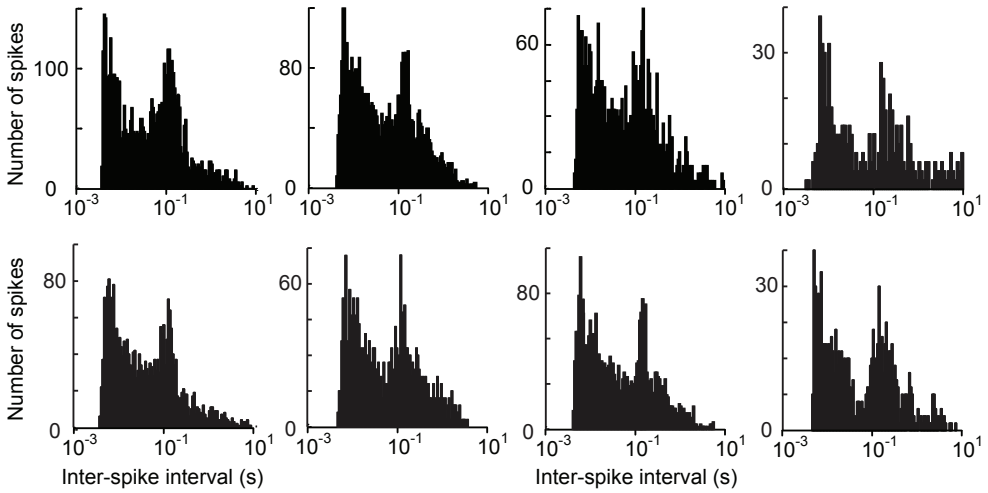
Supplementary Figure 1 | Photograph of the virtual reality setup. A head-restrained mouse runs on an air-supported spherical treadmill. An image from a projector is projected onto a toroidal screen via a reflecting mirror and an angular amplification mirror (AAM). Water rewards are delivered through a lick tube. Electrophysiology setup is not shown. See Methods and Fig. 2A for details.



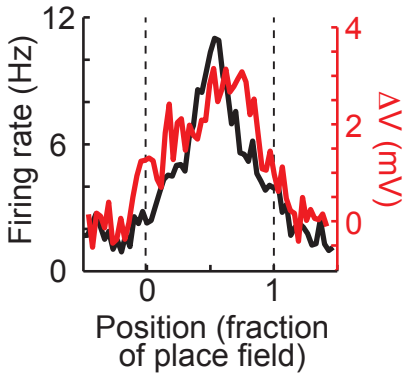
Supplementary Figure 2 | Firing rates, membrane potential depolarizations, and theta power for five place cells recorded intracellularly. a, Firing rates along the virtual linear track for 5 place cells from 5 different animals. The gray boxes indicate the primary place field determined by firing rates. Bottom, vertical lines mark the location along the track of every action potential in the recording. These cells are different than those shown in Figs. 4, 5. **b,** Average baseline membrane potential, excluding action potentials, sorted by position along the track for the five place cells from (a). **c,** Power in the theta-frequency band sorted by position along the track for the whole cell recordings from (a). Power was measured as the squared amplitude of the band-pass (6-10 Hz) filtered membrane potential trace.



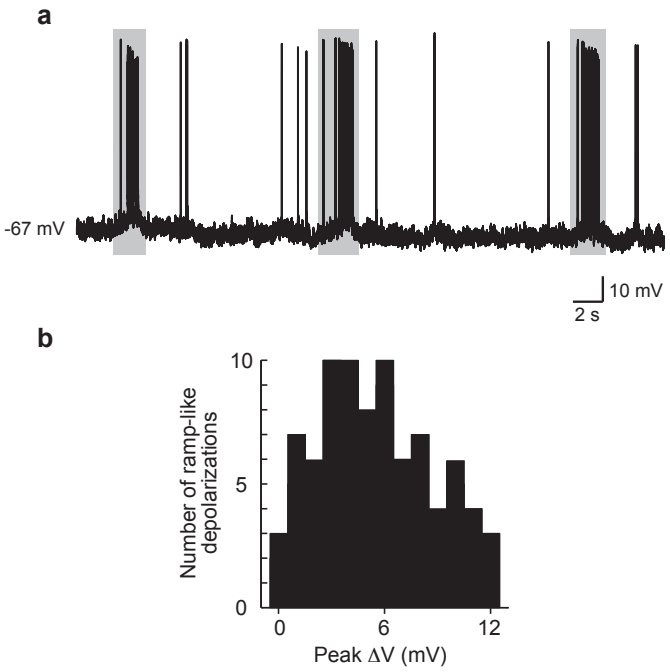
Supplementary Figure 3 | Trajectories and spike positions for two example place cells recorded intracellularly. Left, the position of the animal along the virtual track is shown as a function of time (gray). Red dots indicate the position and time of each spike in the recording. The dots are semi-transparent to illustrate overlapping dots. Right, the position along the track for all spikes from the recording are shown as horizontal lines.



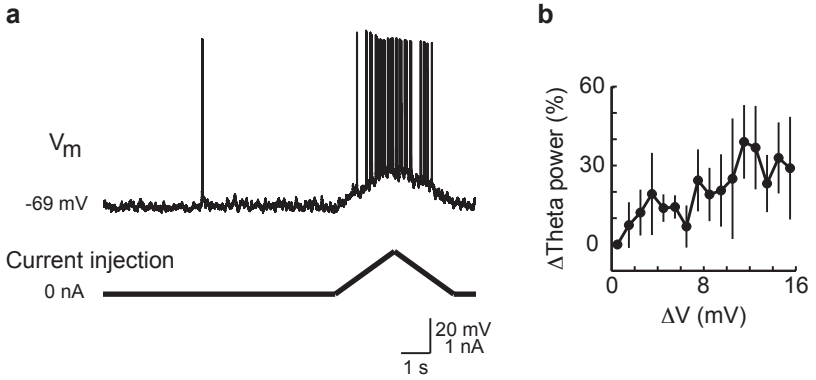
Supplementary Figure 4 | Inter-spike interval distributions from place cells recorded intracellularly. The time axis is plotted on a log scale.



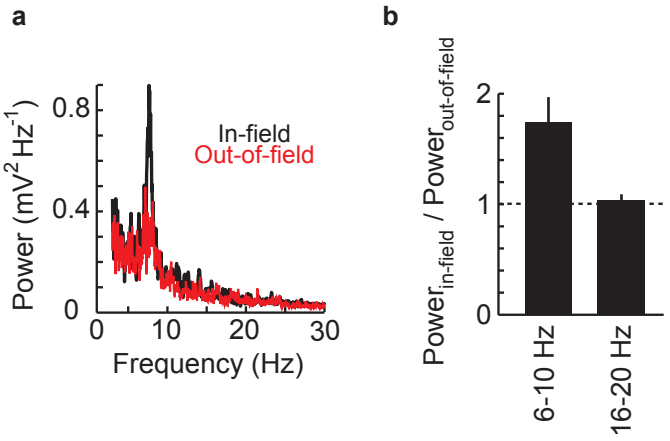
Supplementary Figure 5 | Firing rates (black) and membrane potential depolarization (red) for direct runs through the place field. Data are taken from Fig. 4e. To compare across cells, the position values in the place field were normalized. The values are averaged over 8 cells, including 84 complete runs through the place field.



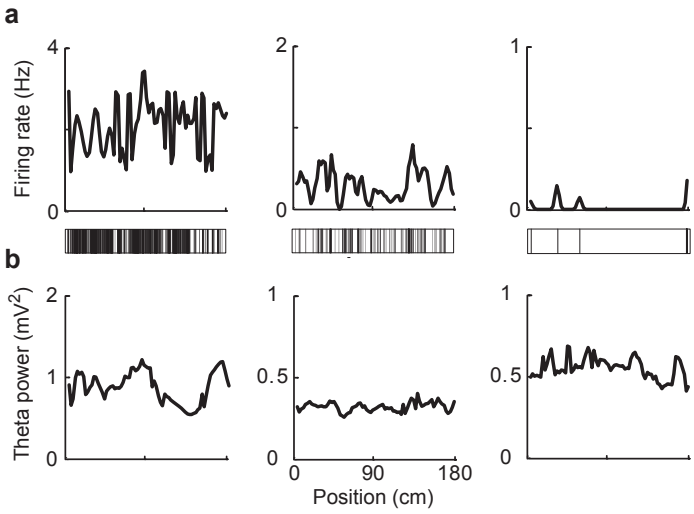
Supplementary Figure 6 | Ramp-like depolarizations during place field traversals. a, Example membrane potential trace. Gray boxes indicate the place field. **b,** Histogram of peak membrane potential changes (ΔV), excluding action potentials, during complete runs through the place field. Data are from 84 runs from 8 cells.



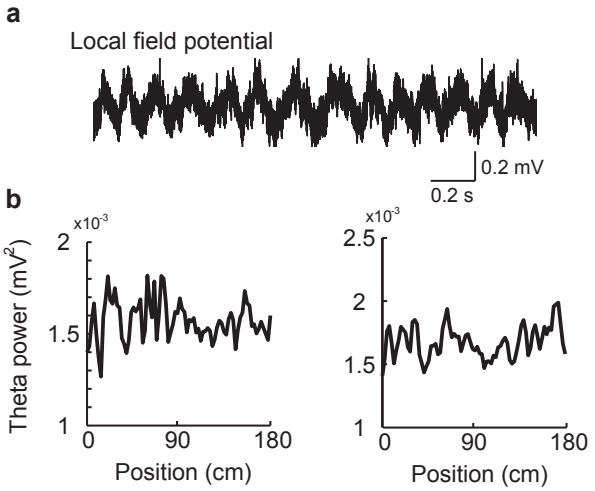
Supplementary Figure 7 | Membrane potential theta oscillations during ramps of depolarization induced by current injections. a, Example membrane potential trace. Ramps of current were injected (4 s duration, 1-1.5 nA peak) following 11 seconds without any current injection. **b,** Changes in theta power as a function of depolarization level. ΔV is the membrane potential at a given point minus the mean baseline membrane potential. ΔV values were grouped into 1 mV bins; the value is plotted at the center of the bin. Theta power was measured as the squared amplitude of the membrane potential trace filtered between 6-10 Hz. ΔTheta power was calculated as the theta power minus the theta power in the $0 < \Delta V < 1$ mV bin and plotted as percentage. Error bars indicate mean ± sem. n = 6 putative pyramidal cells and 1 place cell from 3 mice. Data were consistent between the place cell and the non-place cells.



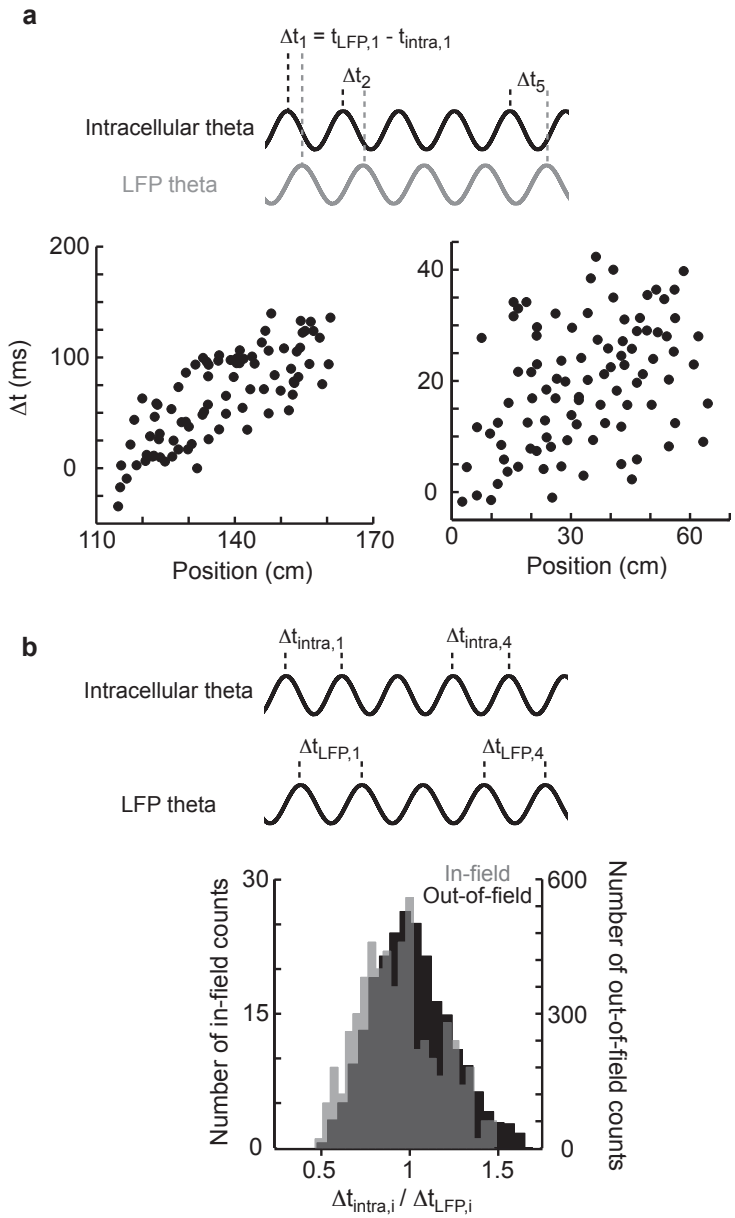
Supplementary Figure 8 | Spectral analysis of intracellular membrane potential recordings. a, Example power spectrum from a single cell for epochs inside (black) and outside (red) the place field. Spectra were obtained using multi-taper spectral analysis. **b,** Ratio of power during epochs inside the place field to power during epochs outside the place field for bands from 6-10 Hz and 16-20 Hz. Power increased selectively in the theta-band during epochs inside the place field. Error bars indicated mean ± sem. n = 8 cells from 8 mice.



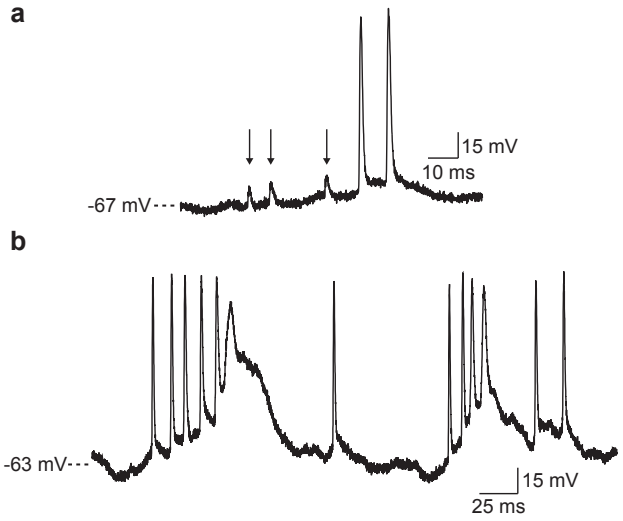
Supplementary Figure 9 | Firing rate and theta power maps for non-place cells. a, Firing rate maps from intracellular recordings for three putative CA1 pyramidal neurons without place fields. Bottom, vertical lines mark the location along the track of every action potential in the recording. **b,** Power in the theta-frequency band sorted by position along the track for the cells from (a). Power was measured as the squared amplitude of the filtered (6-10 Hz) membrane potential trace.



Supplementary Figure 10 | LFP theta oscillations. a, Example LFP recording filtered between 2 Hz and 10 kHz. **b,** Two examples of theta power maps from LFP recordings. Theta power was measured as the squared amplitude of the LFP trace filtered between 6-10 Hz. LFP theta power was similar at all locations along the virtual track.



Supplementary Figure 11 | Frequency comparison of intracellular theta oscillations and LFP theta fluctuations from simultaneous LFP and whole cell recordings. **a,** Phase shift of intracellular theta oscillations relative to LFP theta oscillations during place field traversals. Δt was defined as the time between the first LFP theta peak in the place field and the first intracellular theta peak, the time difference between the second LFP peak and the second intracellular peak, and so on. Position values are from positions along the virtual track. Examples from 2 cells are shown. **b,** Comparison of the periods of intracellular and LFP theta oscillations. To compare periods in the place field, a ratio of the period of the first intracellular theta oscillation to the period of the first LFP theta oscillation, the ratio of the period of the second intracellular oscillation to the period of the second LFP oscillation, and so on were calculated. Segments of length 3 seconds were analyzed for times outside the place field. Data are from 2 cells from 2 mice.



Supplementary Figure 12 | Example subthreshold phenomena from whole cell recordings. a, Brief, small amplitude spikelets are marked by arrows. **b,** Bursts of action potentials were in some cases followed by prolonged depolarization with broadened action potentials.