Behaviors emerge from computations distributed across many neural circuits. How are these neural circuits joined together into systems? How much does one neural circuit need to know about the dynamics of another to properly interpret its output? At one extreme we might imagine that each brain area must in some sense reverse engineer the circuit that generated its input in order to engage in further computations. On the other extreme, we might imagine a highly plug-and-play system in which individual brain areas know little about each other’s dynamics, and instead merely use some simple agreed upon code to transmit information. In this work, we use the prey capture behavior of the salamander as a model system in which to address these questions. Salamanders are predatory amphibians that catch rapidly moving insects. At the forefront of this behavior, nonlinear circuit dynamics in the retina transform the image of a moving target into a complex pattern of electrical impulses distributed across thousands of ganglion cells. The stimulus which drove the responses of a single ganglion cell is not easily inferred from these spike patterns. Here we demonstrate experimentally that despite these complexities, the position of a small rapidly moving target may be tracked with close to photoreceptor precision by calculating the center-of-mass of the ganglion cell population activity (Fig 1), a quantity that can be estimated with the well known population vector average (PVA). PVA tracking works only for cell types whose response dynamics are characterized by the motion anticipation circuit described by [1]; cell types lacking these dynamics generate noisier estimates with substantial delays to the true target position.

Our results show that a highly complex and nonlinear circuit effectively generates a low-dimensional output that may be decoded with linear methods. Such a simple and fast algorithm is well suited to the task of real-time target tracking. A downstream decoder needs to know only the receptive field center of each ganglion cell -- a parameter easily learned during development. In contrast the temporal dynamics and nonlinearities inherent in retinal encoding may be ignored. However, there is a price to be paid -- we show that this algorithm is robust only for a range of target sizes and speeds that are commensurate with that of the prey captured by the salamander. This suggests that specializations in the salamander for catching moving insects begin in the retina itself, where particular dynamical regimes of individual neural circuits ultimately constrain the sizes and speeds of prey that the salamander can catch most effectively.

Figure 1. Photoreceptor-precision target tracking using populations of ganglion cells. Spike rate data from a population of off-type ganglion cells is used to track a target moving at ~10 deg/s via the population vector average. The population estimate (red) has zero delay with respect to the true position (black), and an RMS error of ~5 photoreceptors (PR). The estimate from the model (blue) has ~1 PR error, representing the noise-free case. Note the characteristic overshoots in the estimate during rapid turns.