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Title: A Number Sense as an Emergent Property of the Manipulating Brain

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Abstract: The ability to understand and manipulate numbers and quantities emerges during childhood, but the mechanism through which humans acquire and develop this ability is still poorly understood. In particular, it is not known whether acquiring such a number sense is possible without supervision from a teacher. We explore this question through a model, assuming that the learner is able to pick and place small objects and will spontaneously engage in undirected manipulation. We further assume that the learner's visual system will monitor the changing arrangements of objects in the scene and will learn to predict the effects of each action by comparing perception with the efferent signal of the motor system. We model perception using standard deep networks for feature extraction and classification, and gradient descent learning. Our main finding is that, from learning the unrelated task of action prediction, an unexpected image representation emerges exhibiting regularities that foreshadow the perception and represen- tation of numbers and quantity. These include distinct categories for zero and the first few natural numbers, a strict ordering of the numbers, and a one-dimensional signal that correlates with numer- ical quantity. As a result, our model acquires the ability to estimate numerosity, i.e. the number of objects in the scene, as well as subitization, i.e. the ability to recognize at a glance the exact number of objects in small scenes. Remarkably, subitization and numerosity estimation extrapolate to scenes containing many objects, far beyond the three objects used during training. We conclude that important aspects of a facility with numbers and quantities may be learned without teacher supervision.