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A unified computational model of the development of object unity, object permanence, and occluded object trajectory perception

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ABSTRACT

The perception of the unity of objects, their permanence when out of sight, and the ability to perceive continuous object trajectories even during occlusion belong to the first and most important capacities that infants have to acquire. Despite much research a unified model of the development of these abilities is still missing. Here we make an attempt to provide such a unified model. We present a recurrent artificial neural network that learns to predict the motion of stimuli occluding each other and that develops representations of occluded object parts. It represents completely occluded, moving objects for several time steps and successfully predicts their reappearance after occlusion. This framework allows us to account for a broad range of experimental data. Specifically, the model explains how the perception of object unity develops, the role of the width of the occluders, and it also accounts for differences between data for moving and stationary stimuli. We demonstrate that these abilities can be acquired by learning to predict the sensory input. The model makes specific predictions and provides a unifying framework that has the potential to be extended to other visual event categories.

1. Introduction

Understanding that our world consists of objects that move coherently on continuous paths and that keep existing even when occluded is an important step in our development. For example, research on the perception of object unity seems to have converged on the result that by roughly four months infants show the ability to interpret a rod moving behind a block as complete although only the rod ends are visible (Johnson & Aslin, 1995; Johnson & Náñez, 1995; Kellman & Spelke, 1983), see Fig. 1. This led some developmental researchers to conclude that the perception of object unity is one of the pieces of "core knowledge" that infants are hypothesized to be innately endowed with (Spelke, 1990). On the other hand, there is evidence that newborn infants are not able to perceive object unity (Slater et al., 1990), which makes it difficult to explain the phenomenon in nativist terms.

Another ability that develops early in infancy is object permanence, i.e. the knowledge that objects that are occluded still exist. Only after a couple of months infants start to show understanding of this phenomenon (Baillargeon, 1987; Baillargeon, Spelke, & Wasserman, 1985). How does this ability develop? A related question is the perception of occluded object trajectories, because in order to be able to do that an infant must be able to know that the occluded object still exists. There is evidence that infants develop this ability in the first six months of their lives (Johnson et al., 2003; von Hofsten, Kochukhova, & Rosander, 2007).

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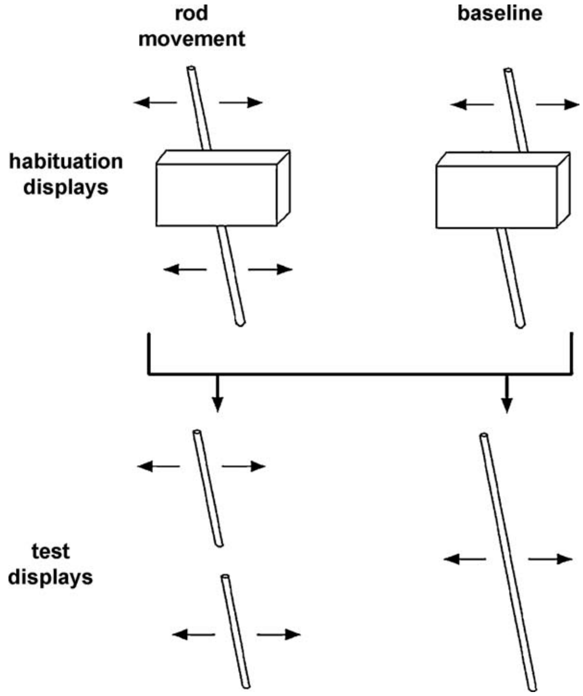

Fig. 1. Displays and design in the study by Kellman and Spelke (1983). Two groups of infants were habituated to the "rod movement" and "baseline" displays, respectively. Then they were tested with the "complete rod" and "broken rod displays appearing in an alternating fashion. The measurement of looking time indicated infants' interpretation of the habituation stimulus.

Most prior studies and theoretical models highlighted only one of these aspects of an infant's perception or cognition. A unified model of those aspects has not been suggested yet, which is important since it can potentially reveal general principles that guide development. Our work is an attempt to make a first step in this direction and to provide a computational model of the development of object unity, object permanence, and occluded object trajectory perception. We present an artificial recurrent neural network that is trained with different occlusion events, learns to represent occluded parts of objects, "perceiving" their unity, can keep the representation over short time intervals such as moving objects disappearing shortly during occlusion. In order to model infants' learning from the environment we introduce a novel modeling feature: the pre-training of the network. During this phase the network is exposed to stimuli that might be analogous to those in an infant's visual environment. Importantly, the network is not pre-trained differently for each experiment since infants are not prepared for the specific studies either.[1] Conversely, we pre-train the network only once and then perform all experiments. After pre-training we expose the network to habituation and test stimuli and compare its performance with infant data. The principle that guides the learning of the network is the prediction of future inputs (Elman, 1990). We show that this approach can successfully explain in total 12 studies covering several aspects of infants' visual development and is also able to make specific predictions for future studies.

1.1. Assumptions

In order for the model to be most helpful for the developmental researcher, we summarize here our assumptions.

1. **Infants acquire the abilities in all three domains by learning spatio-temporal correlations in the environment whereas learning is guided by the same principle: the prediction of future inputs/events**. The way this can be achieved is demonstrated by the model.
2. **During development infants are exposed to both occlusions and unoccluded moving and stationary objects. Objects occur in all combinations, i.e. moving or stationary objects occur in front of and behind other moving or stationary objects**. This assumtion should be obvious since occlusions of moving or stationary stimuli are indeed ubiquitous in our world.
3. **During the habituation studies, infants form interpretations of the habituation stimulus which are compared to (interpretations of) the test stimulus. The difference between them drives their looking time**. This is a broadly

[1] Use of language: throughout the paper the term "experiment" is meant to refer to modeling experiments as opposed to the term "study" which denotes infant experiments.