How the Brain Creates Predictive Models of the Environment

Kaitlyn Tuvilleja

Abstract

Researchers, utilizing technologies like fNIRS (functional near-infrared spectroscopy) on 6-month-olds and EEG (electroencephalography) on infants viewing image sequences, can uncover how young brains craft and apply predictive models to react to events. Adult brain learning is also examined through two types: model-free learning (trial and error) and model-based learning (implementing predictive models). By analyzing data from various age groups, researchers can examine how brains craft predictive models of the environment and leverage those findings for future implications. Dissecting the way the brain constructs predictive models of the environment at distinct ages is crucial for developing enhanced educational practices: this paper examines the development of predictive cognitive models from infancy through adulthood using neurological studies, highlighting their implications for enhancing educational strategies and adaptive behaviors.

Introduction

The way that we react or the choices we make in certain situations is hypothesized to be guided by internal models. This can trigger the body's flight-or-fight response, curiosity, and even hunger. For example, when going to the doctor, the doctor will hit an individual's knee to check their reflexes. What may seem like a knee-jerk reaction is a realization of the brain's predictions about immediate danger, analogous to how a pianist's fingers can predict where the next note is through repetitive practice and auditory exposure to their piece. The brain actively constructs a "call for action" that drives us to continuously shape the brain's internal models (Kayhan et al., 2019). This way, the internal map that the brain has created can guide future actions and decisions. The brain's activation process for predictive models can even be thought of as a construction zone: a place where it actively repairs and reshapes the mental map in response to unexpected changes. To support this theory, O'Reilly's team from Oxford University selected a handful of adults and presented a target object that would change positions. The positions included both predictable locations, learned through repeated exposure and unexpected ones. The study revealed that "Activation in the parietal cortex when an immediate motor response was programmed as participants had to update their internal models to accommodate the change of target locations" (O'Reilly, 2013). When the change was predictable, the parietal cortex, a region of the brain responsible for processing sensory information and coordinating motor responses, quickly adjusted the planned motor commands. However, a surprise triggers the brain's anterior cingulate cortex–an area responsible for updating internal models based on error detection–to activate. Essentially, when unexpected movements occur, they trigger specific brain regions in charge of movement planning and adaptation, evidence to the hypothesis of the brain creating internal models. This factors into the ability to create internal predictive models, and how individuals learn and react to the world through these models, starting from infancy.

Predictive Model Creation in Infants

Current research explores how infants develop the capacity to construct mental maps. As of 2015, a functional near-infrared spectroscopy (fNIRS) study was conducted on infants (Gallagher, 2023). An additional study conducted by E. Kayhan at the University of Potsdam demonstrated that at 6 months old human brains already create a predictive model of the environment. More specifically, "after a learning period, when images were unexpectedly omitted, infants showed activation in the occipital cortex, as if an image was presented, suggesting that they generated predictions about the visual input"(Kayhan et al., 2019).

Researchers were interested in how babies process and adapt to change when prompted by unfamiliar environments. To explore this, they conducted a study with sixty 9-month-old infants. Dr. Kayhan and his team had predicted that "if participants formed predictions based on the repeated observations of the predictable stimuli, they would show a prediction error response when their predictions were violated by the unexpected appearance of the cues" (Kayhan et al., 2019). The study involved showing pictures to the babies and would utilize a system that combined sound and brainwave monitoring (audio-visual EEG). The pictures featured a bee, but the sequence changed to test the babies' predictions. First, the babies were shown repetitive images of a bee (expected sequence). This established a control data set for the scientists. Next, the babies were then shown a predictable surprise which included a bee image followed by an image that could be associated with the bee (i.e. a flower). Finally, the babies were shown an unexpected sequence where the bee image was followed by an image that wouldn't make sense (i.e. a truck). Scientists expected that babies' brains would be more surprised if a pattern was not followed, inducing a stronger electrical response called an Nc wave.

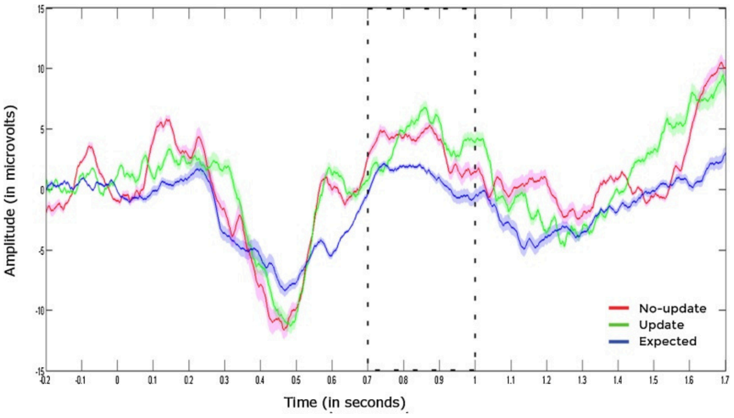

Figure 1. Shows the brain signal from the vertex of the head for the different trial types. The update line shows the highest amplitude meaning the brain produced a stronger Nc wave with the update trial than no-update and expected (Kayhan et al., 2019).

Before the experiment, researchers had predicted that babies would portray a weaker Nc wave (less electrical activity) by seeing the repeated bee images. NC waves detected whether attention was suppressed during the trials (if infants didn't pay attention during trials). Interestingly enough, there was not a significant difference in Nc wave strength between the update and no-update trials within the enclosed section (Fig. 1). This shows that infants might be processing given information more deeply than expected, almost challenging previous knowledge on how infants create predictive models of the environment.

These results can potentially be incorporated in lower education fields, potentially setting a foundation for surprise-based learning. Teachers can implement some surprise or novelty in learning experiences that could benefit children's learning. For example, allowing for more open-ended questions can encourage students to explore different approaches to problem-solving scenarios, sparking curiosity toward unexpected results. By honing in on a child's ability to create predictive models, educators can create more effective and engaging learning practices that foster critical thinking and problem-solving skills.

Predictive Modeling in Adults

However, before revamping academic frameworks based on children's predictive models of the environment, understanding the brain's decision-making is essential. In part, adult brains can learn from reinforcement learning: model-free and model-based (Otto et al., 2015). Model-free RL directly uses past experiences to figure out what actions are rewarding, while model-based RL builds a mental map of how the world works and uses this map to decide what action to take. To further explore this phenomenon, scientist Gläscher strived to find how predictions are created through "trial-by-trial neural signals that reflect the dynamics of this learning" (Gläscher, 2023).

The study consisted of 18 Caltech adult students with normal vision) and no neurological or psychiatric conditions (20/20 and not colorblind). Within two sessions, researchers examined how participants developed optional decisions in a reward-based environment.

The first session involved participants to observe pre-determined choices without rewards. From this, researchers were able to measure state prediction errors (SPEs) – the difference between predicted and actual outcomes – and reward prediction errors (RPEs) – surprises associated with unexpected rewards. By examining the errors, researchers were able to gauge the participant's initial understanding of the system. The second session gave participants the liberty to implement their own choices with the potential of a reward. This tested whether patients could utilize the knowledge in the previous session. Researchers revealed that 13 out of the 18 participants were successfully able to employ model-based learning to execute optimal choices. Suggesting a clear preference for constructing predictive models over trial and error approaches. Participants acquired optimal decision-making through model-based learning which is illustrated through their ability to adapt to the system's modifying tasks, even when rewards were provided. This would demonstrate the idea that "participants would acquire knowledge about the transition probabilities during session 1, despite the absence of any rewarding outcomes. This state knowledge can therefore be only acquired through model-based learning, potentially updated via an SPE" (Gläscher, 2023).

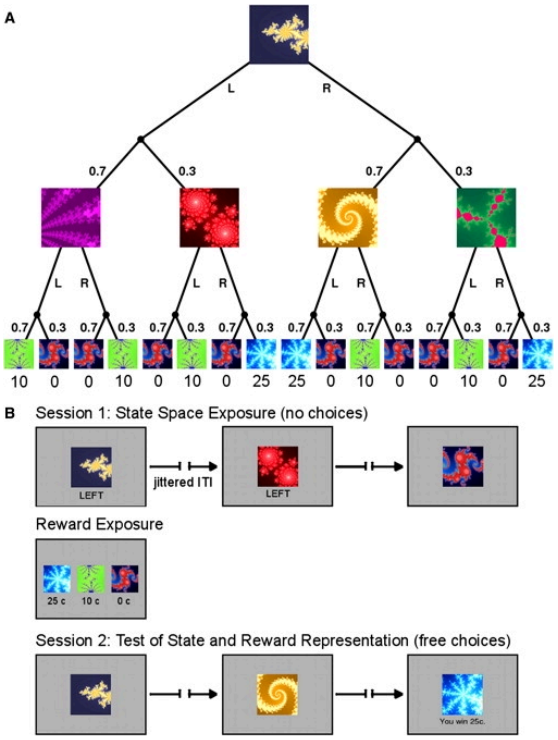

Figure 2. Illustration of the decision-making process of scientist Gläscher and his research team at CalTech's study on model-free reward learning and model-based reward learning (Gläscher)

Future Implications for Learning

Like infants, these findings can be used to configure educational plans for students. As children grow older, their brain develops. To aid these developments, it should be important to continue implementing lessons that can be designed to build upon and challenge these predictive abilities.

Brains do not inactively experience the world but actively work to construct models to predict what will happen next.

This “auto-pilot” function, through its remarkable plasticity, continues to refine its predictive models. Research on infants illustrates the ability to effectively detect unexpected events and update models accordingly. Meanwhile, in part, adults utilize model-free and model-based learning for decision-making. With knowledge of children and adult brain plasticity, educators can leverage these traits to create more engaging learning environments and foster groundwork for adult learning styles. These findings in plasticity hold the potential for unlocking new opportunities for personalized cognitive training programs for children. For example, educational practices can be designed to refine and challenge a student’s predictive models. These implications can be extended to older individuals, as well. With this new profound knowledge of brain plasticity, the possibilities are truly invigorating.

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