A new theory of learning integrates cognitive psychology and systems biology

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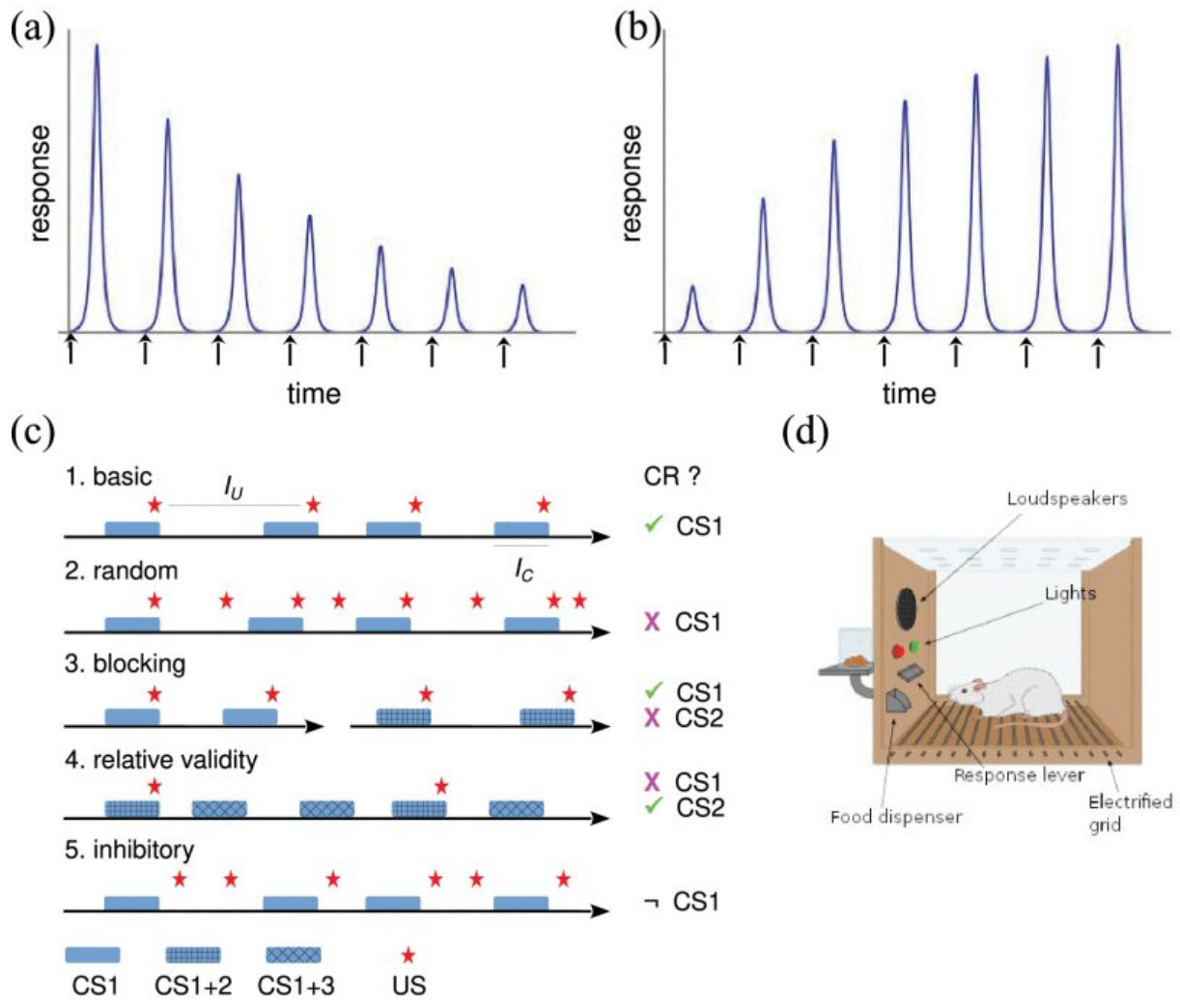

Forms of learning. (a) Habituation. Hypothetical illustration, showing diminishing responses to repeated stimuli (arrows). For additional properties, see [26]. (b) Sensitization. The opposite effect to habituation, in which the response

increases. (c) Classical conditioning, adapted from [27, Box 1]. The right-hand column shows whether or not a CR develops to the indicated CS. Protocol 1 is the traditional Pavlovian one in which the CS (CS1, blue bar), such as a tone or a light, is paired with the US (red star), shown here at a fixed delay from CS onset. I_U and I_C denote the US–US interval and the CS duration, respectively. In protocol 2, the US are presented at random with equal probabilities of occurring with or without the CS, and a CR does not develop. Protocols 3 and 4 are cue competition schemes involving multiple CSs. Protocol 3 has two phases: in the first phase, a CR is established to CS1; in the second phase, the compound stimulus CS1+2 is presented with the US, but a CR to CS2 does not develop. In protocol 4, CS1 is always presented as a compound with either CS2 or CS3, and the US occurs only for CS1+2. A CR develops to CS2 presented in isolation but not to CS1. In protocol 5, the CS is never paired with the US, but an inhibitory association still arises (see text). (d) Instrumental conditioning, showing a Skinner box, in which an organism can be given pleasant (food) or unpleasant (shock) reinforcement, depending on its responses (lever) to various stimuli (light and tone); illustration taken from the Wikipedia entry for Operant Conditioning Chamber under the CC BY-SA 3.0 license. Credit: *Proceedings of the IEEE* (2022). DOI: 10.1109/JPROC.2022.3162791

Many neuroscientists, medical researchers and engineers specializing in artificial intelligence have been trying to understand the neural mechanisms underpinning learning. Although studies have unveiled some vital aspects of these mechanisms, numerous questions remain unanswered.

Jeremy Gunawardena, a researcher at Harvard Medical School, recently introduced a new perspective on learning that merges ideas from the field of cognitive psychology with biological observations. His paper, published in *Proceedings of the IEEE*, highlights some aspects of learning that could set biological organisms apart from computers and machines.

"My interest in learning arose partly from a study we had undertaken

previously in which we showed that the single-cell protozoan, Stentor roeseli, exhibits a complex hierarchy of avoidance behaviors when it is irritated with a jet of particles," Jeremy Gunawardena, one of the researchers who carried out the study, told Phys.org. "This behavior was first described by American biologist Herbert Spencer Jennings around 1900, but it had been considered non-reproducible."

In their past studies, Gunawardena and his colleagues showed that the Jennings' findings were right. More specifically, they found that a single cell is potentially capable of far more complex learning behavior than had previously been considered possible.

Inspired by these findings, Gunawardena initiated a collaboration with one of his colleagues at Harvard, Sam Gershman, who conducted extensive research focusing on the mechanisms of learning. Their work specifically examined how learning occurs in single cells.

"The collaboration with Sam Gershman led to my survey paper in *Proceedings of the IEEE*," Gunawardena said. "Its primary objective was to suggest a definition of learning in information-theoretic terms that was not restricted to animals like us and to set out the evidence from various domains in biology for the existence and significance of learning outside the nervous system."

In his recent paper, Gunawardena describes learning as a broad and universal process pertaining to all living systems, including different animal species, but also potentially plants. He thus feels that a reliable characterization and description of this process could inform research in various fields. For instance, it could greatly contribute to the field of systems biology, adding to existing theoretical perspectives, which largely focus on molecules and their organization.

"We tend to think of cells as complex molecular machines,"

Gunawardena said. "The idea that cells are capable of learning—of forming internal models of their external environments and using those models to guide their behavior—gives them a form of 'agency' that most machines lack and that gets us closer to what it means to be 'living.' Finally, unraveling these 'internal models' could be very useful if we want to exploit cells in a therapeutic manner, for instance, as we are trying to do in immunotherapy."

If confirmed experimentally, the interesting ideas introduced by Gunawardena could offer a fresh and valuable perspective on how countless living organisms learn and survive. Several studies have already hinted at the possibility that plants or specific cells, such as T cells (i.e., crucial components of the immune system), can "learn" based on the stimuli they come in contact with.

"We now have to show that this perspective is real by doing the experimental work and this is what the collaboration with Sam Gershman is about," Gunawardena added. "At present, we are focusing on one of the simplest forms of learning, habituation, which is observed extraordinarily widely in biology, from animals like us to individual cells , and which exhibits some characteristic properties, despite vastly different underlying mechanisms. However, we still do not have a theory that explains this universality nor do we have compelling explanations of how habituation works at the molecular level, which is what we are trying to do now."

More information: Jeremy Gunawardena, Learning Outside the Brain: Integrating Cognitive Science and Systems Biology, *Proceedings of the IEEE* (2022). DOI: 10.1109/JPROC.2022.3162791