

Embracing multiple definitions of learning

Andrew B. Barron^{1,*}, Eileen A. Hebets^{2,*}, Thomas A. Cleland³, Courtney L. Fitzpatrick⁴, Mark E. Hauber⁵, Jeffrey Stevens^{6,7}

* indicates shared first authorship

Affiliations:

1. Macquarie University, Department of Biological Sciences, North Ryde, NSW 2109, Australia
2. School of Biological Sciences, University of Nebraska, NE 68588, USA
3. Department of Psychology, Cornell University, Ithaca, NY 14853, USA
4. National Evolutionary Synthesis Center, Durham, NC, 27708, USA
5. Department of Psychology, Hunter College and the Graduate Center, City University of New York, NY, 10065, USA
6. Department of Psychology, University of Nebraska, NE, 68588, USA
7. Center for Brain, Biology and Behavior, University of Nebraska, NE, 68588, USA

Address for correspondence:

Dr. Mark E. Hauber, Department of Psychology, Hunter College and the Graduate Center, City University of New York, NY, 10065, USA; mhauber@hunter.cuny.edu

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Abstract

Definitions of learning vary widely across disciplines, driven largely by different approaches used to assess its occurrence. These definitions can be better reconciled with each other if each is recognized as coherent with a common conceptualization of learning, while appreciating the practical utility of different learning definitions in different contexts.

The challenges of defining learning

Learning is a major focus of research in psychology, neuroscience, behavioral ecology, evolutionary theory, and computer science, as well as many other disciplines. Despite its conceptual prevalence, definitions of learning differ enormously both within and between these disciplines, and new definitions continue to be proposed [1]. Ongoing disputes over the definition of learning generate uncertainty regarding the boundaries of the learning concept, and confuse assessments about which phenomena genuinely constitute learning. These disputes impair transdisciplinary collaboration and synthesis between conceptually related fields. Many of the definitions in use by these different disciplines, however, can be aligned with a common ‘umbrella concept’ of learning that can be applied across disciplines by considering learning simply as the processing of information derived from experience to update system properties [2-5]. Many of the definitions also have clear practical utility in that they reflect a variety of approaches to determine whether or how learning has occurred. We argue that embracing the multiple definitions defined by individual subfields (Supplementary Table 1) — while simultaneously recognizing their shared relationship to this umbrella concept—will facilitate the integration of neurophysiological, psychological, computational, and evolutionary approaches to learning.

The difficulty of establishing a single satisfactory scientific definition for learning has long been recognized [6]. Perhaps owing to this difficulty, many contemporary psychology and neuroscience textbooks avoid defining learning altogether, preferring instead to explain specific experimental subtypes of learning (such as operant conditioning or habituation) for which it is easier to offer an experimentally supported definition (Supplementary Table 1). A weakness of this approach, of course, is that it discourages engagement with the complexity of the learning concept and its manifestations within different areas of study.

While the specific definitions of learning can vary substantially among fields and even within fields (Supplementary Table 1), most contemporary theoretical considerations of learning view it as a structured updating of system properties based on processing of new information [2-5]. This concept of learning can operate across disciplines. It does not necessarily imply specific mental states, specific cognitive processes or, processing by neurons. It does not limit learning to complex brains: learning can be instantiated in machines or reflex arcs. It emphasizes that learning is not behavioral change; however, changes in behavior, neural systems, or other elements of a system’s performance all can be useful and practical experimental methods to assess whether learning has occurred.

Despite this general underlying conceptual consensus, there is a wide range of highly specified definitions of learning that vary between disciplines. These variations arise out of the endeavours of the experimental scientist. Because learning is a concept of information processing, it can rarely be measured directly: instead, it is often inferred to have taken place by changes in the (biological,

artificial, or virtual/computational) system's properties or performance. For this reason a range of pragmatic definitions of learning bound the concept in such a way that it can be addressed experimentally [1, 7]. Many define learning as a change in behavior, and some define learning as changes in the mechanisms that enable behavioral change (Supplementary Table 1). These pragmatic definitions vary between disciplines and have merit and utility in different experimental circumstances. By appreciating the situational advantages of these different perspectives, and by describing how the term is being employed in a specific context, scholars of learning can minimize confusion within fields of study and facilitate the meaningful translation of studies of learning across the disciplines.

Learning as a change in behavior

Learning is commonly defined as behavioral change. Early on, Skinner [6, 8], promoted this approach by arguing that, since learning is usually determined by assessing behavioral change, defining learning as the behavioral change or altered behavioral outcome *per se* eliminates the need for speculative inference about (hidden) underlying processes. Likewise, De Houwer [1, 7] has more recently advocated for defining learning as behavioral change because this 'functional' approach is more verifiable and generalizable than mechanistic definitions, which require direct knowledge of internal processes. Similar functional definitions of learning are most common in disciplines that focus on the evolution of behavioral outcomes and their consequences, including evolutionary and ecological research (Supplementary Table 1). For instance, mathematical models of evolution that include changes in behavior due to learning most often take a functional approach and define learning as behavioral change, because—rather than being concerned with underlying physiological processes—they are concerned with the ultimate effects of the phenotypic changes caused by learning. Learning can be modelled simply as non-genetic inheritance (e.g. song learning from parents) [9] or as within-generation plasticity of a behavioral phenotype (e.g. song learning from peers) [10]. Notably, while such models make few assumptions about mechanisms, they nonetheless contribute to mechanistic understandings of learning, its ecological distribution, and its evolutionary consequences.

However, defining learning as behavioral change suffers from significant limitations. Domjan [11], for example, has argued that when defining learning as altered behavior, it is both practically and philosophically difficult to disentangle how much of a given behavioral change results from learning and how much may result from other factors, such as altered motivation, physiological changes, or muscle fatigue, maturation or damage [11, 12]. For this reason, some definitions of learning require changes in specific physiological mechanisms that support learning in order to clarify the distinction between learning and other possible causes of behavioral change (e.g., spraining an ankle and walking more slowly thereafter) [11]. The limitation of these mechanistic definitions is that they require identification and measurement of the underlying physiological mechanisms of learning. Accordingly, such definitions of learning occur frequently in the psychological and neural sciences (Supplementary table 1) [5, 11].

As an alternative strategy to distinguish the effects of learning from other factors that could affect behavior, authors often attach various riders to behavioral definitions of learning to constrain the definition. Many of these qualifiers are negative, yielding lengthy discussions of what forms of behavioral change do not reflect learning. But the most common positive qualifier is that learning depends on 'experience'.

Learning and experience

Experience is strongly linked to the learning concept since experience is assumed to be the source of the information that is learned [4, 5]. Whereas experience is part of most definitions of learning (Supplementary Table 1), it is rare to find a scientific definition of experience, or discussion of what experience is [13]. Furthermore, the definitions that do exist recapitulate the flaws of some learning definitions. For example, experience has been defined as an environmental event that is perceived by an organism and capable of altering behavior [12]. However, the experience of a startling noise may effect a behavioral response without this response being considered learning [1]. Thus, learning may depend on experience, but not all experiences will be learned.

Moreover, the requirement that the event must be perceived by the organism to be considered experience has been criticized on functional grounds for blurring the lines between the sensation of detectable environmental events and the inference of cognitive processing [14]. This is particularly problematic for animal behavior research, which frequently assumes but does not test internal mental states and events for non-human animals. These problems are reduced if experience is considered simply as a source of information. Viewed in this way, experience does not presuppose any particular mental events.

Is it necessary to know what has been experienced in order to claim that learning has occurred? As Rescorla [5, 15] has clearly argued, it can be very misleading to assume, rather than test explicitly what is being learned from any experience. For example, classical conditioning theorists originally considered learning to be a process by which a behavioral response transferred to a conditioned stimulus, whereas the contemporary perspective recognizes classical conditioning as learning the relationship between stimuli [5]: a radical change in perspective of what is learned in classical conditioning. For a small number of established laboratory neuroscience protocols with model systems and controlled stimulus presentation, there has been good experimental analysis of what is being learned. For ethological or ecological data about learning in the wild, however, it is often uncertain which environmental events are salient to the animal, which convey information, or precisely what has been learned. Although the terms “experience-dependence”, “behavioral plasticity” or “induced behavioral change” appear increasingly in place of “learning”, we believe this is not constructive. There is no compelling reason to limit the use of learning to situations where the nature of the experience is assumed. To do so would invite serious errors of interpretation, and inhibit transdisciplinary syntheses of learning by fragmenting the discussion of clearly related phenomena.

An integrative perspective on learning

As with other complex concepts such as “fitness” and “gene”, there is no single definition of “learning” that can best serve all scientific purposes, or satisfy all fields and researchers. Disciplines differ in their specific definitions of learning for pragmatic reasons, but it is possible to reconcile most of these definitions by reference to a common theoretical framework: learning as a structured updating of system properties based on the processing of new information. Accordingly, acknowledging the different meanings of learning and being clear on how the term is being used in specific studies are the most effective ways to facilitate transdisciplinary research.

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Table S1. Conceptual and pragmatic definitions of learning surveyed from different disciplines

CONCEPTUAL DEFINITIONS: LEARNING AS THE PROCESSING OF INFORMATION OR EXPERIENCE	
Psychology	
“We can divide all learning into (1) learning by trial and accidental success, by the strengthening of the connections between the sense-impressions representing the situation and the acts—or impulses and acts—representing our successful response to it and by the inhibition of similar connections with unsuccessful responses; (2) learning by imitation...”	Thorndike 1911/2000 [1]
“Learning is a relatively stable unspecified change within an organism that makes a change in behaviour possible; that is due to experience; and that cannot be accounted for in terms of reflexes, instincts, maturation, or the influence of fatigue, injury, disease or drugs”	Chance 1979 [2]
“Learning refers to the process by which an animal (human or non-human) interacts with its environment and becomes changed by this experience so that its subsequent behaviour is modified”	Hall 2003 [3]
“The process of acquiring new and relatively enduring information, behaviour patterns or abilities characterised by modification of behaviour as a result of practice, study or experience”	Breedlove et al 2007 [4]
“In a representational theory of learning, the brain computes a representation of the experienced world, and behavior is informed by that representation. By contrast, in associative theories of learning, which dominate neurobiological thinking, experience causes a plastic brain to rewire itself to make behavior better adapted to the experienced world, without the brain’s computing a representation of that world”	Gallistel 2008 [5]
“[...]learning is a process of change that occurs as a result of an individual's experience”	Mazur 2013 [6]
“Learning is a process by which an organism benefits from experience so that its future behaviour is better adapted to its environment”	Rescorla 1988 [7]
Cognitive Psychology	
“Learning is any process that modifies a system so as to improve, more or less irreversibly, its subsequent performance of the same task or of tasks drawn from the same population.”	Langley and Simon 1981 [8]
“...learning is conceived in terms of the storage of information in memory as a consequence of any experience the individual might have had.”	Medin 2001 [9]
“Learning and memory involve a series of stages. Processes occurring during the presentation of the learning material are known as "encoding" and involve many processes involved in perception. This is the first stage. As a result of encoding, some information is sorted within the memory system. Thus, storage is the second stage. The third (and final) stage is retrieval, which involves recovering or extracting stored information from the memory system.”	Eysenck and Keane 2010 [10]
“The [incidental] acquisition of knowledge about the structural properties of the relations between objects or events.”	Buchner and Wippich 1998

[11]

Neuroscience

“Learning is the process of information input and processing as well as storage, and, on the other hand it is a product which changes in the behaviour of an animal due to experience”	Korte 2013 [12]
“We define memory as a behavioral change caused by an experience, and define learning as a process for acquiring memory.”	Okano, et al. 2000 [13]
“Learning is the process by which we acquire knowledge about the world, while memory is the process by which that knowledge is encoded, stored, and later retrieved.”	Kandel, et al. 2000 [14]
“Learning is the process of acquiring new information.”	Rudy 2008 [15]
“[...]learning is the capacity to change behaviour as the result of individual experience in such a way that the new behaviour is better adapted to the changed conditions of the environment”	Menzel 2013 [16]

Behavioral Ecology

“that process within the organism which produces adaptive change in individual behaviour as a result of experience”	Thorpe, 1943 [17]
“The process which produces adaptive change in individual behaviour as the result of experience. It is regarded as distinct from fatigue, sensory adaptation, maturation and the result of surgical or other injury.”	Thorpe 1951 [18]
“[...]learning can be defined as a process by which long lasting changes in behaviour are acquired by experience”	Sitter 1999 [19]
“[...]learning involves the acquisition, storage and retrieval of information that can potentially affect behavior”	Bekoff 2004 [20]

Machine Learning

“The capacity... to acquire or develop new knowledge or skills from existing or nonexisting examples for the sake of optimizing performance criterion.”	Alpaydin 2004 [21]
“A system is said to learn if it can acquire (synthesize) declarative knowledge from data and/or it displays performance/competence improvement through practice”.	Neri and Saitta 1997 [22]
“[Learning is] the acquisition of structural descriptions from examples.”	McQueen and Holmes 1998 [23]
“[Learning is] the process of forming general concept definitions by observing specific examples of concepts to be learned.	Haglin et al 2005 [24]

LEARNING DEFINED AS BEHAVIORAL CHANGE

Psychology

“[...]the acquisition, maintenance, and change of an organism's behavior as a result of lifetime events”	Pierce and Cheney 2008 [25]
“[...]more or less permanent change in behaviour that occurs as a result of	Kimble 1961 [26]

practice”	
“[...]change in behavior that occurs as the result of practice”	Dewsbury 1978 [27]
“[...]specific and only partly reversible change [in behavior], often related to a positive or negative outcome”. “Experience can change behavior in many ways that manifestly do not involve learning”	Staddon 1983 [28]
“[...]changes in the behavior of an organism that are the result of regularities in the environment of that organism”	De Houwer et al. 2013 [29]
Neuroscience	
“[...]any fairly persistent change in behavioral attributes produced by the action of experience on the central nervous system”	Krasne 1976 [30]
“[...]a change in the behavior of an animal as a consequence of the animal’s experience”	Delcomyn 1998 [31]
“Learning is a change in an organism’s behaviour as a result of experience”	Kolb & Whishaw 2011 [32]
“[...]a relatively permanent change in behavior that results from experience”	Kolb & Whishaw 2014 [33]
Behavioral Ecology	
‘[...]a change/modification in behaviour with experience’	Shettleworth 1984 [34]; van Alphen and Let 1986 [35]; Szentesi & Jermy 1990 [36]; Vet et al. 1990 [37]; Stephens 1993 [38]; Barron 1999 [39]
“a reversible change in behaviour with experience”	Papaj & Prokopy, 1986 [40]
No longer willing to define learning. Instead, offer criteria to specify learning	Papaj & Prokopy, 1989 [41]
1. The individual’s behavior changes in a repeatable way as a consequence of experience	
2. Behavior changes gradually with continued experience	
3. The change in behavior accompanying experience wanes in the absence of continued experience of the same type or as a consequence of a novel experience or trauma	
“Learning is the adaptive modification of behaviour based on experience”	Alcock 2005 [42]
“a change in state due to experience”	Shettleworth 2010 [43]
“Learning is the modification of behaviour due to stored information from previous experience”	Breed 2012 [44]

Machine Learning

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| "A computer program is said to learn from experience E with respect to some class of tasks T and performance measure P, if its performance at tasks in T, as measured by P, improves with experience E" | Mitchell 1997 [45] |
| "Things learn when they change their behaviour in a way that makes them perform better in the future." | Witten and Frank 2005 [46] |
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LEARNING DEFINED AS CHANGES IN BEHAVIORAL MECHANISMS

Psychology

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| "[...]the process by which a relatively stable modification in stimulus-response relations is developed as a consequence of functional environmental interaction via the senses" | Lachman 1997 [47] |
| "[...]an enduring change in the mechanisms of behavior involving specific stimuli and/or responses that results from prior experience with those or similar stimuli and responses" | Domjan 2010 [48] |
| "[...]a long-term change in mental representations or associations as a result of experience" | Omrod 2012 [49] |
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Neuroscience

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| "[Learning is] either a case of the differential strengthening of one from a number of more or less distinct reactions evoked by a situation of need, or the formation of receptor-effector connections de novo; the first occurs typically in simple selective learning and the second, in conditioned-reflex learning" | Hull 1943 [50] |
| "Learning is a manifestation of the malleability of the nervous system because it is a change in the behavior of an animal based on experience. Memory refers to the stored experience and to the process by which it is stored. Memory is a requirement for learning." | Delcomyn 1998 [31] |
| Offer no definition of learning – rather provide mechanistic definitions of specific learning subtypes, <i>e.g.</i> habituation. | Carew 2000 [51]; Schwartz, et al. 2002 [52]; Kalat 2007 [53]; Reznikova 2007 [54]; Squire, et al. 2008 [55]; Gluck, et al. 2008 [56] |
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Behavioral ecology

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| "[...]the acquisition of neuronal representations of new information" | Dukas, 2009 [57] |
| "Learning is a change in the nervous system manifested as altered behavior due to experience" | West-Eberhard 2003 [58] |
| "Learning is a specific change or modification of behaviour involving the nervous system as a result of experience with an external event or series of events in an individual's life" | Grier 1992 [59] |
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