Rios, Luis A. and Rachinskii, Dmitrii and Cross, Rod (2017) On the rationale for hysteresis in economic decisions. Journal of Physics: Conference Series, 811 (1). ISSN 1742-6588 , http://dx.doi.org/10.1088/1742-6596/811/1/012012

This version is available at https://strathprints.strath.ac.uk/60552/

On the rationale for hysteresis in economic decisions

Luis A Rios

Wharton School of Business, University of Pennsylvania, USA

E-mail: `luisrios@wharton.upenn.edu`

Dmitrii Rachinskii

Department of Mathematical Sciences, The University of Texas at Dallas, USA

E-mail: `dmitry.rachinskiy@utdallas.edu`

Rod Cross

Department of Economics, University of Strathclyde, UK

E-mail: `rod.cross@strath.ac.uk`

Abstract. In the social sciences there are plausible reasons to postulate that hysteresis effects are important. The available evidence, however, is predominantly at the macro level. In this paper we review the evidence regarding hysteresis in the neural processes underlying human behavior. We argue that there is a need for experimental and neuroimaging studies to fill the gap in knowledge about hysteresis processes at the micro level in the social sciences.

1. Introduction

The term hysteresis, derived from the Greek "to come behind", entered the lexicon of science to describe effects on electromagnetic fields in ferric metals that remain after a magnetizing force has been applied then removed: "these curves exhibit, in a striking manner, a persistence of previous state, such as might be caused by molecular friction the curves for the back and forth twists are irreversible, and include a wide area between them... to this action... the author now gives the name Hysteresis" ([1], p. 22).

Subsequently hysteresis effects have been identified, or postulated to exist, in a wide range of areas of inquiry, ranging from the original physics context to biology, electronics, materials science, cognitive neuroscience through to social sciences such as economics (see the entries in [2]). The mathematics of hysteresis as a general systems property has been formalised [3], showing that systems containing heterogeneous elements at

the micro level, which respond non-linearly to changes in inputs, have outputs that contain a selective, erasable memory of the non-dominated extremum values of the input innovations experienced (see [4] for a graphical exposition).

In social sciences such as economics it has been argued that hysteresis is pervasive: "the fact that the individual's continuous adjustment to changing price and income conditions changes his tastes seems so obvious that in the past economists mentioned it in passing, if at all... in order to determine the equilibrium of the consumer... we need to know... this particular hysteresis law" ([5], p. 126); see [6] for a review that stresses the distinction between ontological and epistemological hysteresis. In major areas of economic inquiry such as the effects of recessions and booms on subsequent economic activity [7, 8], the determinants of unemployment [9] and the effects of foreign exchange rate changes on international trade [10], hysteresis effects have been identified at the aggregate or macro level. Unlike many of the areas outside the social sciences in which hysteresis effects have been discovered, however, in the social sciences the evidence at the macro level has been supported more by speculation as to the behavior at the micro level that might give rise to hysteresis than by direct experimental evidence. In the original ferromagnetic context, for example, the discovery of hysteresis in the behavior of the electromagnetic field as a whole has been complemented by experimental evidence of non-linear responses by heterogeneous elements at the molecular level in the form of such as Barkhausen effects. The challenge, then, for hysteresis explanations in the social sciences is to see if tests can be conducted to see if the hysteresis in human behavior postulated to exist can be identified experimentally.

To pave the way for finer grain investigations of hysteresis in economics and the social sciences, the contribution of the present paper is to speculate as to the processes within the human brain that might give rise to hysteresis in economic and social decisions. To do this we discuss the brain memory capacity problem raised by [11] and some evidence from neuroscience that suggests the existence of hysteresis in at least some of the neural processes at work within the human brain. It is not necessarily the case that finer grain accounts of hysteresis will have greater explanatory power than accounts based on a higher level of aggregation [12], but the potential for enhanced understanding and new discoveries is there.

In the mainstream neoclassical model in economics, economic systems are characterised by equilibrium processes in which equilibria are pinned down by exogenously given consumer preferences and production relationships, and so not influenced by the paths taken towards the equilibria. This neoclassical model in economics was originally inspired by metaphors drawn from Newtonian mechanics or conservative fields of force [13], and later reformulated on the basis of axioms in which conservation and reversibility properties hold. The existence of hysteresis in neural processes would be difficult if not impossible to reconcile with this framework of analysis. Hysteresis offers a different "constitutive" metaphor [14] for understanding the behavior of economic systems. In what follows we discuss some features of what is known about neural processes that might give rise to hysteresis in economic decisions. This is best regarded as an attempt to identify pieces in the formidable jigsaw puzzle that is the human brain. These might be useful in future investigations in the burgeoning sciences of experimental economics (see [15] for a methodological review) and neuroeconomics

(see [16] for a survey).

2. The von Neumann puzzle

In his posthumously published comparison of computers and human brains, von Neumann raised the question of how the storage capacity of the brain could cope with the sensory inputs experienced during a lifetime [11]. He used 10^{10} as an estimate of the number of neurons in the human brain. If it is assumed that each neuron has 10^3 connections with other neurons via axons and dendrites, and that each of the resulting synapse connections can hold one bit of information, this yields $10^{10} \times 10^3 = 10^{13}$ bits of information that the human brain can hold. The estimate of the sensory input during a lifetime is derived by assuming that all the neurons and their synapse connections can be receptors of external or internal stimuli. The estimate of a feasible receipt of stimuli at 14 per second, gives a stimuli input of 14×10^{23} bits per second. The assumed lifetime was 60 years, or about 2×10^9 seconds. The stimuli would not necessarily be retained in active parts of the brain, but, if no stimulus could be erased, the estimate of the "memory" capacity required to cope with a lifetimes stimuli is $14 \times 10^{13} \times 2 \times 10^9 = 2.8 \times 10^{23}$ bits. Thus there is a discrepancy of the order of 10^{10} bits between the brain's storage capacity and the external and internal stimuli experienced during a lifetime ([11], pp. 63–64, with the 10^3 synapse adjustment for axonal and dendritic connections from [17], p. 176).

The obvious way to reconcile the stimuli experienced during a lifetime with the brain's capacity to cope with such stimuli is to postulate that not all stimuli are stored in the brain's memory. Landauer [18] used four approaches to estimating the external stimuli that are stored during a human brain's lifetime. The first two are based on reading recall and picture recognition, and follow von Neumann's assumption that all recorded information is entered into long-term memory and is kept permanently. For the concentrated reading task the reading rate of 3 words per second was accompanied by a commitment to long-term memory of 0.4 bits per word read, giving an input to long-term memory of 1.2 bits per second. A linear accumulation over a 70-year lifetime yielded an estimate of 1.8×10^9 bits of information held in the human memory. A somewhat similar calculation based on picture recognition involved an input into long-term memory of 2.3 bits per second, cumulating to 3.4×10^9 bits over a lifetime. A third estimate allowed for an overwriting form of memory loss, giving a 1.4×10^9 bits over a lifetime estimate. A fourth estimate uses a word dictionary analogy applied to 15 domains of knowledge to produce an estimate of 0.5×10^9 lifetime bits of information ([18], p. 481, Table 1). A major limitation of the Landauer estimates is that they deal only with declarative/explicit memories and do not consider procedural/implicit memory processes within the brain.

Matters become more complicated once the distinction between short and long-term memory is introduced. An effective memory system has to not only store information but also encode and retrieve that information. This requires the brain to respond to the internal stimuli involved in encoding and retrieval operations. The working memory model ([19], Ch. 3) provides an account of how the brain's architecture intermediates between short and long-term memory. A central executive controls attention and coordinates the following: a visuo-spatial sketchpad that sets up and manipulates images

from the external stimuli received; a phonological loop that is responsible for inner "speech" within the brain; and an episodic buffer that integrates information retrieval from long-term memory with the current demands of working memory. Experiments suggest that working memory capacities are quite small, subjects finding it difficult to remember sequences of numbers that contain 5 or more digits ([19], p. 44). Cowan [20] reviews the literature on the "magical number 4 in short-term memory".

Further complications arise once the assumption that long-term memories are "hard wired" is dropped. The traditional view was that short-term or working memories were labile until consolidated into long-term memory after a lapse of time, measured in hours for "synaptic consolidation" and longer for "systems consolidation" for memories that are initially hippocampus dependent ([21], 2010, p. 27). There is, however, evidence that long-term memories can also become labile during the process of retrieval. The conjecture is that process of retrieval leads to a process of reconsolidation of long-term memories [22]. This would add to the processing capacity demands on the brain, arising from the reconsolidation of long-term memories.

Finally, but by no means exhaustively, the von Neumann estimate would have to be adjusted for differences in synaptic plasticity and strength. Bartol Jr, Bromer, Kinney, Chirillo, Bourne, Harris and Sejnowski [23] found that the excitory synapses on dendritic spines of hippocampal pyramidal neurons had a minimum of 26 different synaptic strengths. In terms of the binary bits of information used in the von Neumann calculations, these estimates translate into 4.7 bits that can be stored at each synapse as synaptic strength, that is $2^{4.7} \approx 26$. Adjusting for synaptic strength differences not only raises the estimate of the memory capacity of the brain, but also the von Neumann type estimate of the stimuli that the brain's receptors could accommodate over a lifetime. In this area of research "one of the most intriguing findings is that the size of the synaptic response is not invariant, but can be altered by a variety of homo- and heterosynaptic factors such as past patterns of use or modulatory transmitters" ([24], p. 1).

3. Hysteresis in neural processes

The von Neumann puzzle was that, in the Heraclitean flux of a lifetime, the human brain is subject to external and internal stimuli that would, if all such stimuli were stored in its memory, exceed its encoding, storage and retrieval capacity. The most obvious way to resolve this puzzle is to postulate that not all stimuli received are encoded or stored in the memory. In relation to short-term memories that last for only a few minutes this would mean that not all stimuli received find a response in terms of changes in synaptic strength. In relation to long-term memories that require the cellular synthesis of new proteins, and involve short-term memory changes that are stabilized or consolidated to last for days or years ([24], p. 7), this would mean that not all changes in synaptic strength trigger the synthesis of new proteins. In this section we discuss whether thresholds of the type involved in the elemental "lazy relay" model of hysteresis could help resolve the von Neumann puzzle. It is interesting that von Neumann himself entertained this possibility: "it has been proposed to assume that the thresholds – or, more broadly stated, the stimulation criteria – for various nerve cells change with time as functions of the previous history of that cell ... thus frequent use of a nerve cell might lower its threshold, i.e. ease the requirements of its stimulation, and the like... if this were true,

the memory would reside in the variability of the stimulation criteria... it is certainly a possibility, but I will not attempt to discuss it here" ([11], p. 64).

The possibility that hysteresis processes are at work in the brain, and can help resolve von Neumann's puzzle, was pursued in work conducted at the Weizmann Institute of Science in Israel in the 1960s on the physical changes that might account for the memory imprint of a pattern of external stimuli on a chemical system. Katchalsky and Neumann ([17], p. 178) argued that "the requirements of a sufficiently fast record with low expenditure of energy, and the storage of the record after the stimulus is over, severely limit the choice of possible physical mechanisms... a long retention of the memory imprint is necessary to allow the induction of further consolidation in permanent structures... it seems that this imprint could be based on equilibrium states which are a priori time-independent and stable... but any equilibrium processes are a priori excluded, since equilibrium states are independent of path, and therefore memoryless... the only simple mechanism which seems to answer all biophysical requirements is that of hysteresis".

Following the Cox, Jones, Marsh and Peacocke [25] discovery of molecular hysteresis in acid-base titration of RNA, Neumann and Katchalsky [17] studied the relationship between protonation in a synthetic polyribonucleide, poly (A) and poly (U), combination proxy for natural RNA and acid-base titration. The resulting proton binding curves are illustrated in Figure 1. The curves describing the degree of proton uptake, α, as a function of the acid-base titration, pH, exhibit the loops typical of systems with hysteresis. The α values for ascending values of pH are lower than those for descending values; and a given value of the output, α, can be associated with a range of values for the input stimulus, pH. This can give rise to a form of temporary inertia or metastability in which the output memory can coexist with a range of input stimuli. These hysteresis loops are of the type observed by Ewing [1] for electromagnetic fields in ferric metals.

The calculations underlying the von Neumann puzzle assume that sensory perception is an inevitable reflexive reaction to being exposed to a stimulus. In contrast, neuroimaging experiments suggest that "perceiving objects in our physical environment... can be formulated as a dynamic process of selecting and matching a sensory input to that predicted on the basis of higher-order representations... perceptual awareness results from this constructive process, and it is essential to stabilize percepts against continuous and often critical shifts of low-level stimulus parameters, such as contrast levels, that occur at the level of the sensory receptors" ([26], p. 660). This means that the brain does not respond to all sensory inputs, perceptual awareness only being triggered once critical or threshold values of the stimuli are reached. If there were a single critical value for a stimulus to trigger perceptual awareness, small variations around this value would involve the expenditure of energy associated with frequent changes in awareness. Instead the evidence suggests that perceptual hysteresis pertains, there being a range of values of the stimulus over which perceptual awareness will not change. This is the "lazy relay" archetypal form of hysteresis.

Figure 2 illustrates perceptual hysteresis for an experiment in which the intensity of the image of the letter k is contrasted relative to a background by slowly increasing the dot density defining the letter. The experimental subjects were asked to press a key when the letter k became clearly perceived, illustrated as the "pop out" value a in Figure 2. The image intensity was then slowly reduced from a supra-threshold level.
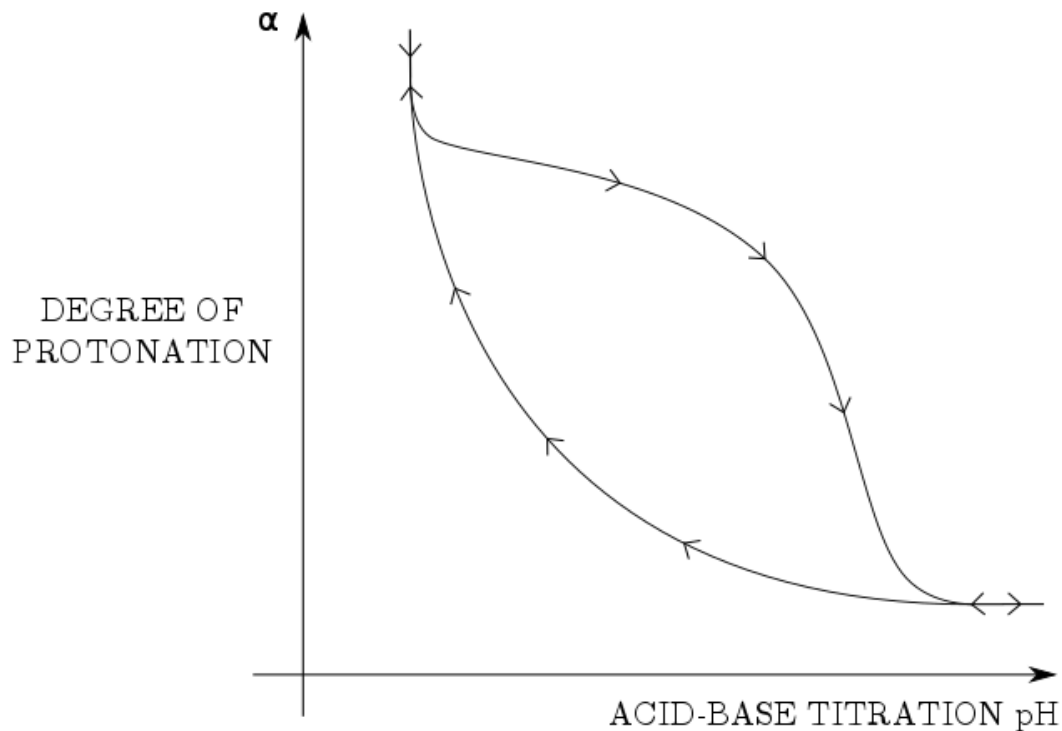
Figure 1. Hysteresis in proton binding curves. Source: Adapted from Katchalsky and Neumann (1972, p. 180, Figure 4).

Instead of the perception of k dropping out when the image intensity reached a, the "drop out" only occurred when the lower image intensity at b was reached. Hence there is a range of stimuli from b to a over which perceptual awareness does not change. As in the "lazy relay" hysteresis archetype, perceptual awareness within this range will depend on whether the percept stimulus has been approached from above or below. The neuroimaging procedures revealed that the fMRI signal changes associated with neural hysteresis were associated with the "higher" ventral lateral occipital, inferior parietal, premotor and inferior prefrontal cortex areas of the brain, and not in the early visual areas; and that the signal changes indicated greater activity when the experimental subjects were first exposed to a cycle of variation of image intensity than in subsequent repetitions of the cycle ([26], p. 659).

The existence of perceptual hysteresis might provide a clue as to how motion aftereffect illusions arise. The standard instance of this type of perceptual illusion is the waterfall effect [27]. Gaze in a concentrated way at a waterfall for about 30 seconds, and then refocus on the rockface at the side of the waterfall: the rockface appears to be moving upwards, an illusion that can last for up to a minute. This illusion may arise from the stabilization of the perception of water falling downwards by perceptual hysteresis, and the initially unsuccessful attempt by the brain to reconcile this with the
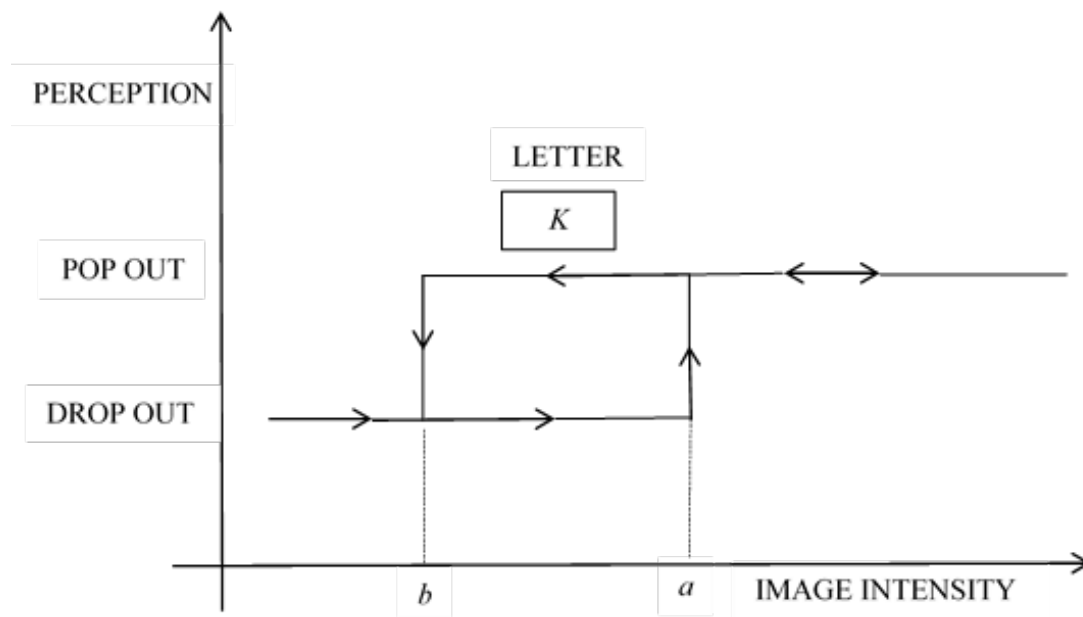
Figure 2. Perceptual hysteresis. Source: Adapted from Kleinschmidt, Büchel, Hutton, Friston and Frackowiak (2002, p. 660, Figure 1).

already stabilized perception of a stationary rockface.

Mach [28] proposed that the brain uses classification devices to cope with what would otherwise be a bewildering variety of sensory stimuli. It is now uncontroversial to postulate that prior knowledge is combined with sensory stimuli to shape perception. In cognitive neuroscience a distinction has been drawn between two effects that previous experience can have on perception: hysteresis and adaptation [29]. Hysteresis is seen as an attractive effect that sensitizes the brain to perceive the same again, whereas adaptation is a repulsive effect whereby something different is perceived. Schwiedrzik et al. [29] report fMRI evidence that the two processes map into different cortical networks: a widespread network of higher-order visual and fronto-parietal areas of the brain deal with the perceptual stabilization involved in hysteresis; whereas only early visual areas of the brain are involved in the perceptions of something different involved in adaptation. They argue that such a division of labor is efficient, or in Mach's term "economical". Hysteresis paves the way to predict what will happen next, stabilizing perception in the face of the flux of low-level stimuli which require no further processing. This allows the early visual areas of the brain to specialize on the extraction of new information from stimuli that are notably different, and so require the detailed and sensitive representations involved in adaptation. This is a Bayesian world in which hysteresis effects are the embodiment of prior probabilities about the sensory world, and changes in sensory experience represent adaptation effects that modify the likelihood functions.

4. Discussion

In the social sciences some, if not all, of the processes under study have been seen as haunted by a memory of the past such as can be found in systems with hysteresis. The evidence cited in support of such conjectures has tended to be at the macro level, with the micro processes that might give rise to hysteresis being more a matter of speculation than established fact. In this paper we have considered some evidence regarding neural processes that might help pave the way for experimental studies that would help fill this gap regarding hysteresis processes at the micro level in the social sciences. Is there perceptual hysteresis in the social sphere? Are the decisions made within organizations characterised by hysteresis? And so on.

An obvious first line of inquiry would be to conduct laboratory experiments to test for the existence of hysteresis in the decisions made by experimental subjects. A basic experiment would involve varying an incentive, such as the pay rate for a work task, upwards to discover the pay rates at which the subjects switch from a leisure to a work mode; and then varying the pay rate downwards to find the pay rates at which the subjects switch back from the work to the leisure mode. If the pay rates at which the subjects switch from leisure to work modes are significantly higher than those for switching back to leisure from work, once the work mode has been experienced, this would provide direct experimental evidence of a lazy relay hysteresis relationship between incentives and behavior. The way would then be clear for finer grain neuroimaging investigations, of the areas of the brain that are activated when switching behavior occurs, for example.

The von Neumann type estimates of brain capacity reviewed in this paper suggest that there is a marked discrepancy between the external and internal stimuli a human brain is exposed to during a lifetime and the brain's capacity to encode, store and retrieve this information when guiding behavior. It might well be the case that this discrepancy is resolved within the brain by the use of economy principles in which hysteresis plays an important role. As an anonymous referee has pointed out, hysteresis may also convey evolutionary advantages. Strategies yielding behavior that changes too frequently, or not often enough, in relation to challenges presented by the environment, are not conducive to survival. So hysteresis in the neural processes underlying behavior may have emerged by natural selection.

References

[1] Ewing J A 1881 On the production of transient electric currents in iron and steel conductors by twisting them when magnetized or magnetizing them when twisted *Proceedings of the Royal Society of London* **33** 21–23
[2] eds G Bertotti and I D Mayergoyz 2006 *The Science of Hysteresis* (Oxford: Academic Press) vol 1
[3] Krasnosel'skii M A and Pokrovskii A V 1989 *Systems with Hysteresis* (Berlin: Springer)
[4] Mayergoyz I D 1991 *Mathematical Models of Hysteresis* (Berlin: Springer)
[5] Georgescu-Roegen N 1971 *The Entropy Law and the Economic Process* (Cambridge MA: Harvard UP)
[6] Elster J 1976 A note on hysteresis in the social sciences *Synthese* **33** 371–391

[7] Cross R, McNamara H and Pokrovskii A V 2012 Memory of recessions *Journal of Post Keynesian Economics* **34** 409–425

[8] Cross R, McNamara H, Pokrovskii A V and Rachinskii D 2008 A new paradigm for modelling hysteresis in macroeconomic flows *Physica B: Condensed Matter* **403** 231–236

[9] Darby J, Cross R and Piscitelli L 2006 Hysteresis and unemployment: a preliminary investigation The Science of Hysteresis eds G Bertotti and I D Mayergoyz (Oxford: Academic Press) vol 1 chapter 8 pp 667–699

[10] Amable B, Henry J, Lordon F and Topol R 1991 "Strong" hysteresis: an application to foreign trade *OFCE Working Paper* **9103** (Paris: OFCE)

[11] Von Neumann J 1958 *The Computer and the Brain* (New Haven: Yale UP)

[12] Jackson F and Pettit P 1992 In defence of explanatory ecumenism *Economics and Philosophy* **8** 1–21

[13] Mirowski P 1989 *More Heat than Light* (New York: Cambridge UP)

[14] Klamer A and Leonard T C 1994 So Whats an Economic Metaphor? *Natural Images in Economics* ed P Mirowski (Cambridge UP: New York) chapter 2 pp 20–51

[15] Guala F 2005 *The Methodology of Experimental Economics* (New York: Cambridge UP)

[16] Camerer C, Loewenstein G and Prelec D 2005 Neuroeconomics: How neuroscience can inform economics *Journal of Economic Literature* **43** 9–64

[17] Katchalsky A and Neumann E 1972 Hysteresis and molecular memory record *International Journal of Neuroscience* **3** 175–182

[18] Landauer T K 1986 How much do people remember? Some estimates of the quantity of learned information in long-term memory *Cognitive Science* **10** 477–493

[19] Baddeley A 2004 *Your Memory: a Users Guide* (London: Carlton Books)

[20] Cowan N 2000 The magical number 4 in short-term memory: A reconsideration of mental storage capacity *Behavioral and Brain Sciences* **24** 87–185

[21] Nader K and Einarsson E O 2010 Memory Reconsolidation: An update *Annals of the New York Academy of Sciences* **1191** 27–41

[22] Alberini C M 2011 The role of reconsolidation and the dynamic process of long-term memory and storage *Frontiers in Behavioral Neuroscience* **5** 1–10

[23] Bartol T M Jr, Bromer C, Kinney J, Chirillo M A, Bourne J N, Harris K M and Sejnowski T J 2015 Nanoconnectomic upper bound on the variability of synaptic plasticity *eLife* **4** e10778

[24] Mayford M, Siegelbaum S A and Kandel E R 2012 Synapses and memory storage *Cold Spring Harbor Perspectives in Biology* **4** a005751

[25] Cox R A, Jones A S, Marsh G E and Peacocke A R 1956 On hydrogen bonding and branching in a bacterial RNA *Biochemical Biophysics Acta* **21** 576–577

[26] Kleinschmidt A, Büchel C, Hutton C, Friston K J and Frackowiak S J 2002 The neural structures expressing perceptual hysteresis in visual letter recognition *Neuron* **34** 659–666

[27] Anstis S, Verstraten F A J and Mather G 1998 The motion aftereffect *Trends in Cognitive Sciences* **2** 111–117

[28] Mach E 1959/1897 *The Analysis of Sensations* English edition (New York: Dover Books)

[29] Schwiedrzik C M, Ruff C C, Lazar A, Leitner F C, Singer W and Melloni L 2014 Untangling perceptual memory: Hysteresis and adaptation map into separate cortical networks *Cerebral Cortex* **24** 1152–1164