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Robert Hooke's model of memory

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In 1682 the scientist and inventor Robert Hooke read a lecture to the Royal Society of London, in which he described a mechanistic model of human memory. Yet few psychologists today seem to have heard of Hooke's memory model. The lecture addressed questions of encoding, memory capacity, repetition, retrieval, and forgetting—some of these in a surprisingly modern way. Hooke's model shares several characteristics with the theory of Richard Semon, which came more than 200 years later, but it is more complete. Among the model's interesting properties are that (1) it allows for attention and other top-down influences on encoding; (2) it uses resonance to implement parallel, cue-dependent retrieval; (3) it explains memory for recency; (4) it offers a single-system account of repetition priming; and (5) the power law of forgetting can be derived from the model's assumptions in a straightforward way.

In 1682 the scientist and inventor Robert Hooke (1635–1703) read a lecture to the Royal Society of London on the topic of memory. The lecture is remarkable because it represents one of the earliest and most comprehensive attempts to construct a mechanistic model of a cognitive process, yet it is virtually unknown among psychologists today. The model was published in a collection of Hooke's lectures 2 years after his death (Hooke, 1705/1969), anomalously placed last in a series of talks on the nature of light. (For the title page of Hooke's posthumous works, which gives this lecture greater prominence, see Figure 1.)

Excerpts from Hooke's lecture have appeared in a book on the history of psychiatry (Hunter & Macalpine, 1963); and the psychologist B. R. Singer discussed Hooke's model and its intellectual background in a rather obscure historical journal (Singer, 1979).[1] Neither source is likely to have been read widely by cognitive psychologists. I encountered a two-paragraph description of Hooke's model in a book on the evolution of communication systems (Dyson, 1997), and this was sufficiently intriguing for me to have my university's library assist me in a little archaeology by digging Hooke's posthumous works out of storage. What I uncovered there, obscured by ambiguity, archaic language, and a 300-year gap in cultural background, was a surprisingly complete model of memory.

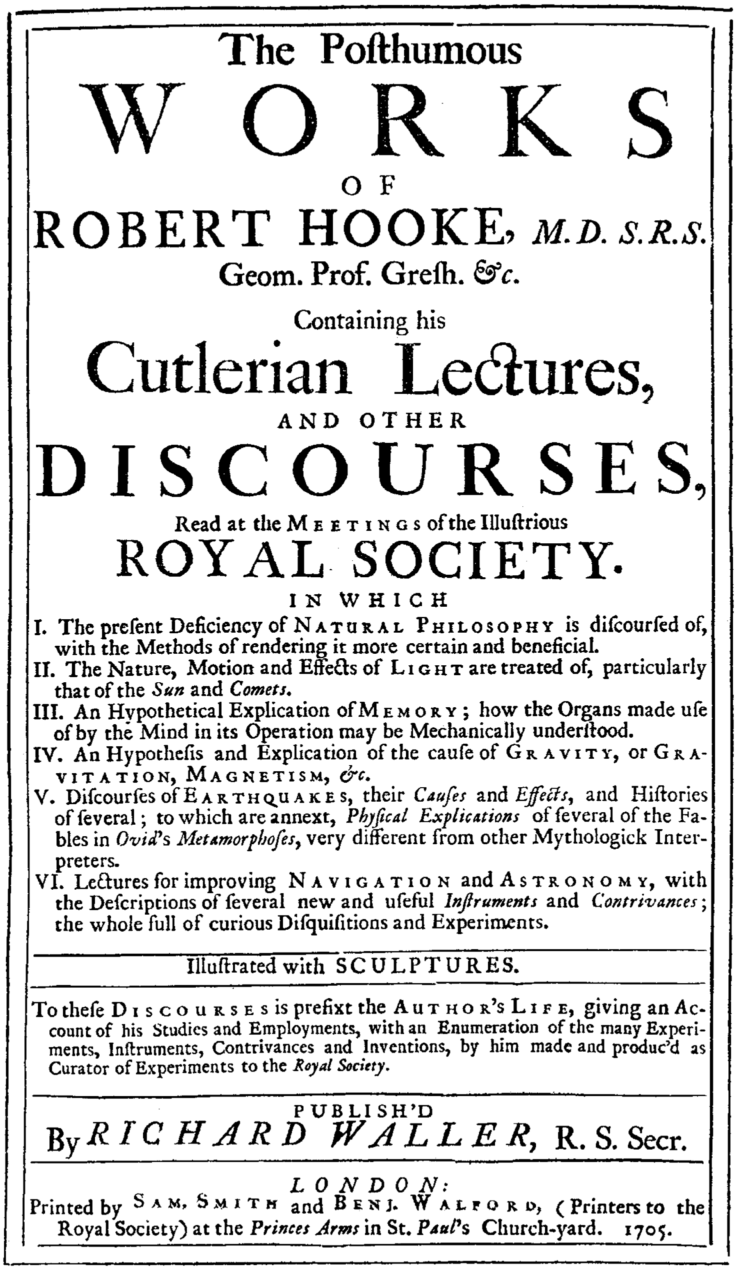
My goal in this article is to make Hooke's model accessible to modern researchers in cognitive psychology. I will present my understanding of Hooke's ideas, together with my impressions of how they are related to later developments in the psychology of memory. This goal necessitates considerable interpretation and reorganization of what Hooke had to say. A certain degree of "hindsight bias" is inevitable in such an effort, and there is surely room for disagreement about exactly what Hooke meant. Readers who wish to decide such matters for themselves are urged to consult the text of the original lecture, although a reasonably good summary can be found in Singer (1979).

Background

Robert Hooke was a central figure in science in the late 17th century ('Espinasse, 1956; Jardine, 1999). He held the posts of Curator of Experiments for the Royal Society of London and Professor of Geometry at Gresham College. After the great fire of London in 1666, he served for a time as City Surveyor and also worked as an architect. Later, some of Hooke's buildings were mistakenly attributed to his friend Christopher Wren. Hooke is credited with inventing the universal joint, the spring scale, the spring-driven pocket watch, and the iris diaphragm now commonly used in cameras. He also contributed significantly to the development of the air pump, the diving bell, the mechanical calculator, various meteorological devices, the reflecting telescope, and the compound microscope. Dyson (1997) describes Hooke's invention of a method of optical telegraphy—the sending and receiving of coded messages via lanterns and telescopes—which became common in Europe by Napoleon's time.

In physics, Hooke is known primarily for his law of the elasticity of springs. But he also made key contributions to the field of optics and to the study of combustion and respiration. In a highly influential book, he presented detailed engravings of organisms and materials as seen with

I thank Douglas J. Herrmann and David J. Murray for helping me locate references to Hooke's lecture, and Myron Rothbart and Michael Anderson for comments on an early version of this manuscript. Correspondence should be addressed to D. Hintzman, Department of Psychology, University of Oregon, Eugene, OR 97403 (e-mail: hintzman@oregon.uoregon.edu).



The Poſthumous
WORKS
OF
ROBERT HOOKE, *M.D. S.R.S.*
Geom. Prof. Greſh. *&c.*
Containing his
Cutlerian Lectures,
AND OTHER
DISCOURSES,
Read at the MEETINGS of the Illuſtrious
ROYAL SOCIETY.
IN WHICH
I. The preſent Deficiency of NATURAL PHILOSOPHY is diſcourſed of, with the Methods of rendering it more certain and beneficial.
II. The Nature, Motion and Effects of LIGHT are treated of, particularly that of the *Sun* and *Comets.*
III. An Hypothetical Explication of MEMORY; how the Organs made uſe of by the Mind in its Operation may be Mechanically underſtood.
IV. An Hypotheſis and Explication of the cauſe of GRAVITY, or GRAVITATION, MAGNETISM, *&c.*
V. Diſcourſes of EARTHQUAKES, their *Cauſes* and *Effects*, and Hiſtories of ſeveral; to which are annext, *Phyſical Explications* of ſeveral of the Fables in *Ovid*'s *Metamorphoſes*, very different from other Mythologick Interpreters.
VI. Lectures for improving NAVIGATION and ASTRONOMY, with the Deſcriptions of ſeveral new and uſeful *Inſtruments* and *Contrivances*; the whole full of curious Diſquiſitions and Experiments.
Illuſtrated with SCULPTURES.
To theſe DISCOURSES is prefixt the AUTHOR's LIFE, giving an Account of his Studies and Employments, with an Enumeration of the many Experiments, Inſtruments, Contrivances and Inventions, by him made and produc'd as Curator of Experiments to the *Royal Society.*
PUBLISH'D
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LONDON:
Printed by SAM. SMITH and BENJ. WALFORD, (Printers to the Royal Society) at the *Princes Arms* in St. *Paul*'s Church-yard. 1705.

Figure 1. The 1705 title page of Hooke's posthumous works.

the compound microscope, and he was the first to describe the cellular structure of plants (Hooke, 1665/1961). Hooke also wrote extensively on earth science, propounding the view that fossils were extinct animals and that Earth's history might be reconstructed from a study of their occurrence in layers. Historians of science have been intrigued by a bitter priority dispute between Hooke and Isaac Newton. Hooke felt that Newton had denied him credit for key aspects of Newtonian theory—particularly for the inverse square law and its application to both celestial mechanics and terrestrial gravitation.[2] It has been argued that Newton engineered, or at least abetted, Hooke's gradual descent into obscurity in the decades following his death. For this and other matters concerning Hooke's astonishingly diverse and productive career, see 'Espinasse (1956). A highly readable account of 17th-century science, including Hooke's role in it, is given by Jardine (1999).

To put Hooke's memory lecture into historical perspective, it took place about 60–70 years after Galileo and Bacon had proposed general rules for the conduct of science, about 50 years after Harvey discovered the circulation of the blood, and about 30 years after Descartes proposed that reflexes—but not the intellect—could be explained mechanistically. Although some things were known about the gross anatomy of the brain, it would be 100 years before Galvani demonstrated the electrical nature of the nerve impulse, and 170 years before Helmholtz measured its speed. It would be about 200 years before Donders (1868) measured the speed of mental processes, before Galton (1880) developed the word-association test (see Crovitz, 1970), and before Ebbinghaus (1885) demonstrated that memory could be studied experimentally and objectively. In comparison with Hooke's lecture, the writings of his contemporary John Locke (1690) were quite sketchy on how memory as a whole might function.

Overview of the Model

Hooke (1705/1969) introduces the topic of his lecture by asking how we apprehend the passage of time. He points out that

> all the Information we have from the Senses are momentary, and only last during the Impressions made by the Object. There is therefore yet wanting a Sense to apprehend Time. . . . Considering this, I say, we shall find a Necessity of supposing some other Organ to apprehend the Impression that is made by Time. And this I conceive to be no other than that which we generally call Memory, which Memory I suppose to be as much an Organ, as the Eye, Ear, or Nose, and to have its Situation somewhere near the Place where the Nerves from the other Senses concur and meet. (pp. 139–140)[3]

In support of the view that memory is material and organic, Hooke argues that memory may be improved, that the formation of memories is impaired during sleep, and that "Memory has been quite destroyed by a Fall, or great Blow upon the Head, by a Fever, or other great Sickness; nay often by Excess of Drinking, all of which affect not the Soul" (p. 140).

Hooke adopts a version of Descartes' dualism. He conceives the soul, or agent of thought, as spiritual or immaterial, and as interacting with the brain at a fixed anatomical location. Unlike Descartes, Hooke declines to specify the locus of interaction, although he says that this is a topic on which "I have much that I may at another time produce" (p. 141). At the point of interaction with the brain, the soul is constantly constructing new memories, each of which is attached to the previous memory in an interlinked chain. Pressure from newly formed memories continually pushes against the older ones, in a sphere that expands outward from the center.

> So that there is as it were a continued Chain of Ideas coyled up in the Repository of the Brain, the first end of which is farthest removed from the Center or Seat of the Soul where the Ideas are formed; and the other End is always at the Center, being the last Idea formed, which is always the Moment present when considered: And therefore according as there are a greater number of these Ideas between the present Sensation or Thought in the Center, and any other, the more is the Soul apprehensive of the Time interposed. (p. 140)

Hooke thus proposes a geometric account of the sense of time. "The greater the number of ideas are that have succeeded any ones formation, the greater is the space of time of which we have a sense" (p. 144); and the apparent recency of an event or idea is represented by a physical distance in the brain. The crucial distance is not measured back along the chain, however, but radially outward from the center of the repository. Thus, "the Notion of Time is the Apprehension of the Distance of Ideas from the Center or present Moment. And so Time comes to be apprehended as a Quantity, and so falls under the Consideration of Geometry and Mensuration" (p. 141). This statement describes a theory of recency judgment—a point to which I will return later. More generally, it reflects a key insight into the possibility of psychophysics and psychological scaling, which no one, including Hooke, followed up at the time.

Hooke elaborates on the basic model in several ways. In what follows, I will concentrate on his explanations of how memories are encoded and stored, how they enable someone to reexperience a previous event, how repetition affects memory, and how forgetting occurs. A surprising number of modern concepts are foreshadowed in Hooke's theory. These include the power law of forgetting, which—I shall claim—can be derived in a fairly straightforward way from the model's geometry. A schematic drawing of Hooke's model, as I understand it, is shown in Figure 2, which depicts the spherical memory store in cross-section.[4] Much of the following discussion may be understood with reference to this diagram.

Functionally, Hooke's model bears some striking similarities to the memory model of the biologist Richard Semon (1919/1923), which has also been celebrated for its obscurity (Schacter, 2001; Schacter, Eich, & Tulving, 1978). An extended discussion of Semon's theory is beyond the scope of this article, but I will mention some of the similarities in passing, and in the Discussion I will try to explain why they exist.

Encoding

One of Hooke's initial concerns is to explain how a material substance can record and subsequently reinstate the details of a previous experience. He assumes the existence of substances sensitive to all "the Elements out of which Ideas are made; among which Variety there are principally five sorts fitted and adapted to receive the Impressions from the five Senses" (p. 141). As examples, he discusses objects that retain and reproduce physical energies even after the original energy source has ended. These include bells, strings, and large vases, which continue to vibrate for a short time after the cessation of a sound, and the "Bononian stone," which retains phosphorescence after exposure to light (for a discussion of the latter, see Singer, 1979, note 29). Such objects literally display "echoic" and "iconic" memory.

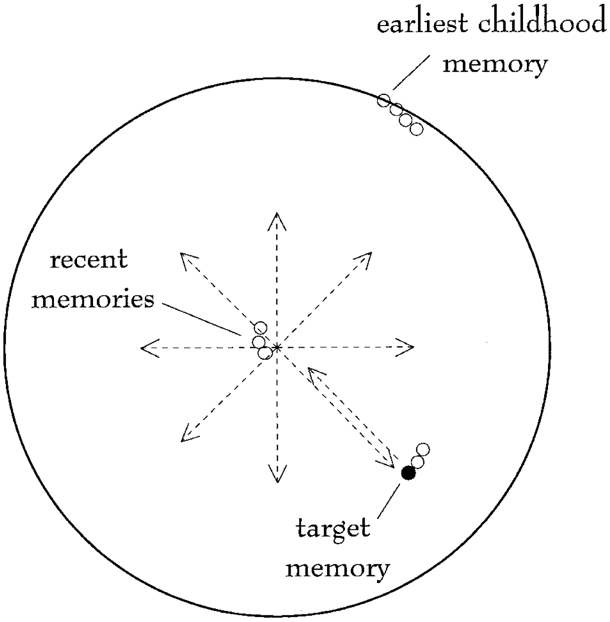

Figure 2. A schematic diagram of Hooke's model. The memory store is a growing sphere, shown in cross-section. The soul interacts with the brain in the center, where it is continually adding new memories to a coiling chain. The oldest memories are on the sphere's outer surface, and newly formed memories are at the center. Activity of the soul is broadcast throughout the sphere (dashed arrows), and memories of similar past activity resonate in sympathy. A target memory of intermediate age (black dot) resonates its contents back to the soul.

Hooke admits that these effects do not last long, "yet [long] enough to shew us a Specimen of a certain Qualification not to be found in most other Bodies, which may yet possibly be done much more powerfully and effectually" inside the body, "where all things are ordered and adapted by the All wise Creator, for the Work to be done" (p. 141).

> As I shall by and by shew, they do and will each of them retain their several impressions long enough to make them sufficient for producing the same Reactions whenever they are again acted upon. And such an Impression I shall prove is again given both by the Soul and by succeeding similar Sensations: For having Potentiality of receiving, and being excited by such Impressions, they do again renew their former Impression, and afresh shew their Power . . . (pp. 141–142)

The substances found in the memory repository are thus able to record impressions and play them back later, when rearoused by similar impressions emanating from the soul's current activity.[5] This occurs "in the same manner as a musical String being moved, does make another String that is in unison or harmonious with it, move also" (p. 145). Obviously in the case of sound, and less obviously in the case of light (Hooke held a wave, or impulse, theory of light), the mechanism of rearousal is one of resonance. Hooke seems to imply that resonance similarly serves to reinstate other sensory and nonsensory components of a remembered experience. It is not uncommon for memory modelers to invoke a resonance metaphor to show how a very large memory store might be rapidly searched in a parallel, content-addressable manner (e.g., Hintzman, 1986, 1988; Ratcliff, 1978; Semon, 1919/1923).

With regard to encoding, Semon's (1919/1923) theory makes for an interesting comparison with Hooke's model. In Semon's theory, memory traces ("engrams") are records of sensory experience, which are rearoused ("ecphorized") when the same sensory experiences reoccur. There is no real top-down processing, because retrieval can be driven only by sense impressions or by reactivated memories of sense impressions (Schacter et al., 1978). In contrast, Hooke's theory is not so constrained:

> Memory then I conceive to be nothing else but a Repository of Ideas formed partly by the Senses, but chiefly by the Soul itself . . . For I conceive no Idea can be really formed or stored up in this Repository without the Directive and Architectonic Power of the Soul; and the Actions or Impressions cease and fail without the concurrent Act of the Soul, which regulates and disposes of such Powers. . . . This Action of the Soul is that which is commonly called Attention. (p. 140)

So Hooke sees encoding as depending on both top-down and bottom-up processing. Moreover, the top-down influence extends beyond the allocation of attention among sensory inputs, to the encoding of elaborations and abstractions. This is shown by Hooke's treatments of thinking and reasoning.

Hooke does not say what he means by thinking, but we may suppose that he intends to explain how one works out a solution to a problem (in Hooke's case, a design for a building or an invention) over an extended period of time. Such thinking is fundamentally an act of the intellect or soul, but its interaction with memory is essential. In Hooke's description, the soul is constantly focusing attention on "this or that part of the Repository, or on this or that Idea placed in it, and at the same time forming new Ideas in the Center of the Repository. . . . And though it doth not every moment make a distinct Idea, yet may it be perfecting of one, and giving new Impressions every moment" (p. 145). In accordance with Hooke's basic assumptions, such new impressions are encoded in a fresh trace at the center of the repository, which subsequently will be available to retrieval. "And when [the idea] again comes to be acted upon by the Radiation of the Soul, all the Impressions or Qualifications thereof become of the Power to affect the Soul with those Impressions which it had formerly received from the Soul" (p. 145). As a result, ruminations on a topic of interest can become more and more elaborate over time.

Hooke next turns to a subcategory of thinking that he calls "reasoning." He does not define the term, but he does say that in reasoning a "Conclusion" is formed "from the comparison of other Ideas which may be contain'd in the *major* and *minor* Propositions" (p. 146). This indicates the sort of deductive reasoning about category membership that Aristotle formalized in the syllogism.[6] For thousands of years, the syllogism was viewed as the paradigmatic framework for logical thought. According to Hooke, reasoning involves the soul's activity in the

> forming of new Ideas from comparing the Re-actions from several Ideas placed here and there in the Repository, and its being sensible of the Harmony or Discord of them one with another, which does produce an Idea wherein all those various Respects are in some means united and impressed upon one and the same Idea. . . . so is the Idea more compleat, as well as more compounded. (p. 146)

In the context of the syllogism, this passage appears to describe the process of abstraction. The comparison of ideas (each possibly derived from many individual events) leads to new ideas that represent abstract categories and their relations. Once such abstract ideas have been stored, they would today be called concepts, generic memories, or semantic memories. Although these ideas are abstract, in Hooke's model they reside in the same store as do memories of concrete events or episodes.

The "harmony and discord" of ideas discussed by Hooke in the foregoing passage also play a role in the theory of Richard Semon (1919/1923; Schacter et al., 1978). Semon distinguished between two kinds of "homophony" or resonance among activated engrams, which he called "nondifferentiating homophony" and "differentiating homophony." In Semon's theory, these processes appear to be largely automatic consequences of the simultaneous activation of traces, whereas in Hooke's theory, the soul directs attention to memories according to its purposes. Thus for Hooke abstraction appears to be an essentially analytic process, whereas it is a more automatic process for Semon.

Obviously, the larger the repository of memories becomes, the more opportunities there are to form elaborations and abstract concepts. Thus Hooke explains one aspect of cognitive development: "This will give some Reason why the younger and first Results of the Actions of the Soul in forming Ideas, are more simple and less perfect, and from whence the Results of the Actions of the Soul in the elder Years, become the more compounded and perfect" (p. 146).

Capacity

With new memories being formed every waking moment, a natural concern is whether there is enough room for them all in the brain. Hooke discusses this issue at some length. First, he proposes traces to be "material and bulky, that is to be certain Bodies of determinate bigness . . . and therefore . . . no two of them can be in the same space" (p. 142). Here, he clearly subscribes to a localist, as opposed to a distributed, view of storage. Although traces are localized, their locations are not fixed. Once formed in the center, each memory packet is relentlessly shuffled outward by pressure from new memories inserted at the head of the chain.

Second, the rate at which ideas are formed may vary from person to person, "So that in some there may be Four of them formed in a second Minute of Time, in others possibly not One in two Seconds of Time." And an average person may store "a thousand Millions of distinct Ideas . . . beginning with the time of the first Advertency of the Child, and continuing to the time of the actual Separation of the Soul and Body at Death" (p. 143). Hooke calculates that in 100 years, at a rate of one per second, a person might store 3,155,760,000 ideas. He then makes a series of deductions from this figure, relating to such factors as sleep, "Infancy, old Age, Sickness and Inadvertency," eventually arriving—none too convincingly—at a greatly reduced estimate of 1,826,200 memories in the brain of a person 50 years old. To argue for the plausibility of this figure, he turns to his studies of microorganisms:

> I see no Reason why all these may not actually be contained within the Sphere of the Activity of the Soul acting in the Center. For if we consider in how small a bulk of Body there may be as many distinct living Creatures as there are supposed Ideas, and every of these Creatures perfectly formed and endued with all its Vegetative and Animal Functions, and with sufficient room also left for it to move it self to and fro among and between all the rest . . . we shall not need to fear any Impossibility to find out room in the Brain where this Sphere may be placed, and yet find room enough for all other Uses. (pp. 143–144)

This seems to be the only aspect of Hooke's lecture to have entered the psychological literature on memory, and then only in garbled form. It appears that the physiologist Albrecht von Haller (1708–1777) used the largest of Hooke's figures to estimate that a 50-year-old's memory would have to contain 205,542 traces per gram of brain tissue. Von Haller thought this preposterous, and he concluded that memories could not be material. Burnham (1888–1889) mentions this, but has Hooke getting the idea from von Haller, who was not born until after Hooke's death. Burnham's error is repeated by Gomulicki (1953).[7] Neither Burnham nor Gomulicki references Hooke's lecture.

Retrieval

As we have seen, for Hooke retrieval was primarily a matter of resonance. Memories are serially chained, but the chain is coiled around the point where the soul interacts with the brain. A serial search of memory is not necessary, because resonance provides parallel access to everything in the repository. Concretely, Hooke compares the soul's relation to the memory store with the Sun's relation to surrounding space:

> The Soul then is . . . the self-moving Principle, which has in it self a Power of radiating every way in Orbem from its Center of being every instant and for ever, and so is always by means of that Radiation every where as it were actually present, in every point of the Sphere of its Radiation, though yet it may be supposed to be more immediately and powerfully present in the Center of its Being. (p. 146)

But the soul also functions like the eye, in its ability to detect "the Re-action of the Ideas" to this outgoing radiation (p. 144). In this way the soul constantly monitors memories for activation. Also like the eye, the soul can select certain objects for the focus of attention. While the soul "has at all times sense of all the Ideas that are there reposed, yet that Sense is but imperfect and confused by reason of their Multitude; yet can it readily exert its Power more particularly and strongly to this or that Idea, according to the Determination of its Will" (p. 145).

It is not immediately clear how the soul could simultaneously have a sense of "all the Ideas" in the memory store. An interpretation that is consistent with Hooke's other assumptions is that the soul is constantly radiating activity onto all the ideas in the store and can sense the ones that are resonating to its current activity. Such an interpretation is generally consistent with what has been called "global matching," as an explanation of the feeling of recognition or familiarity that surrounds an ongoing experience (Clark & Gronlund, 1996). In global matching models such as that of Gillund and Shiffrin (1984), such parallel activation can be followed up by recall of specific items, which corresponds to the soul's focus on particular ideas. Hooke says that focusing on an idea produces "that impression which we are sensible of, when we say, This brings to my Mind, or This puts me in mind, or this makes me remember . . ." (p. 145). Here, he clearly describes the experience of recall or recollection.

By means of its radiation throughout the memory repository, the soul

> becomes sensible of all those Ideas that are yet unwasted within the Repository, feeling as it were their Form, their Resistance, and their Re-action to its Radiations: Partly, I say, only by their lying in the way of the Radiation, and partly also by their re-acting and repercussing a Radiation back upon the Soul. By the Distance of it from this Center the Soul becomes sensible in some measure of the time in which the Idea was made, and how long since it was inserted, there being so many Orbs of later or more inner Ideas formed and lying between them, which have been since inserted. (p. 144)

This is Hooke's answer to the question with which he began his lecture, of how we come to be aware of a remembered event's recency. It would be some 280 years before the first experiments were done on recency judgment (Yntema & Trask, 1963). For a review of research on this topic, see Friedman (1993).

Hooke realized that it was not sufficient to show that a memory's distance from the center would increase with the memory's age; in addition, the soul must have a means of sensing that distance. Further, the soul must be able to avoid confusing old but strongly resonating memories with memories that are recent. To explain how this is done, Hooke uses his analogy with the sun, in a way that seems bizarre to a reader familiar with modern science.

Consider a ray sent out by the sun, which meets an impeding object. "For as any one, and every one Ray it sends forth, does meet with and affect any Body in this way, so consequently must that End of the Ray that touches the Sun, have a greater or less Resistance to be moved forwards . . ." (p. 146) Moreover, this resistance will depend on the "nearness of the impeding or re-acting Object," so the distance can be inferred directly from the resistance. "Next by the number of the Rays that receive Impediment from that Object, there is a manifest Distinction of the bigness of that Object" (p. 146). Because the soul knows the resistance, and hence the distance, the number of rays emanating from the object can be adjusted for distance. In this, Hooke reminds us, the soul demonstrates no more sophistication than does the eye, which uses perceived distance to infer an object's size from its retinal size, or the ear, which can distinguish between the loudness and the distance of a sound's origin.

How precisely does an event's apparent recency—its radial distance from the center—vary with the number of more recent events (which I will refer to as *lag*)? We can derive a recency-judgment function from Hooke's model by thinking of the target trace as lying on the surface of an imaginary sphere, nested inside the overall repository. As is shown in Figure 2, a cross-section of this sphere would be represented by a circle centered on the soul's point of interaction, and passing through the target memory. Traces of events more recent than the target event fill the inner volume of the sphere. The volume of a sphere is of course proportional to the cube of the radius (i.e., $V = \pi r^3$). If we assume for simplicity that each memory trace occupies the same amount of space, it follows that

$$\text{radial distance} = k \cdot \text{lag}^{1/3}, \qquad (1)$$

where k is a constant. Thus, apparent recency should be a power function of actual recency or lag, with an exponent of 1/3.

As it turns out, a logarithmic function has been found to fit recency judgments better than a power function does (Hinrichs & Buschke, 1968). The model is falsifiable in this regard, because the prediction derives directly from the brain's three-dimensional geometry. Free parameters are generally frowned upon in physical science, but this is far less true in psychology (see Roberts & Pashler, 2000). Few memory models are so constrained as Hooke's is, to predict both the form of a curve and its exponent.

Repetition

Two kinds of mechanisms have been proposed to explain why memory improves with repetition. Strength theories hold that repetition increases the potency of an association or memory representation; multiple-trace theories hold that repetition produces redundant representations. Because traces of the soul's present actions are assumed to be laid down at the center of the memory store regardless of how closely they correspond to past ideas, Hooke's model qualifies as a multiple-trace theory. Separate traces representing a repeated idea or recurrent event may be distributed widely in the memory store.

Hooke says nothing about this directly, but information relating to the number of traces that match the soul's current activity would provide it with a basis for judging familiarity or presentation frequency. Judgments of frequency could be based on the summed reactions to the cue of all traces in the memory store (for a formal model of how this might work, see Hintzman, 1988). Alternatively, the soul could estimate the number of spatially disjoint sets of "rays" emanating from the surrounding repository. In the latter approach, the representations of frequency and time would be distinct, in the sense that each remembered event has its own apparent recency. Data consistent with this idea (e.g., Hintzman & Block, 1971) pose problems for strength theories of repetition.

Although Hooke's model implies that temporally distributed repetitions are represented by spatially distributed memory traces, there are at least two senses in which the traces of repetitions are not independent. First, Hooke suggests that resonating traces in memory interact with and help to shape the soul's current activity. The more complete is the memory record, Hooke says, "so is the Soul the better enabled . . . to form new Ideas aright, or rightly to apprehend the thing to be known" (p. 140). This influence of activated traces on current experience suggests a kind of perceptual learning. To the extent that this top-down effect of memory is automatic, it appears consistent with what has been called "transfer-appropriate processing" (e.g., Roediger, Weldon, & Challis, 1989).

Second, even as the soul is laying down a trace of its current activity, Hooke allows that it can strengthen preexisting traces that are compatible with that activity. By "fixing or darting its Radiation more powerfully upon this or that idea placed in the Repository," the soul does more than sense each idea's content. In addition,

> by this second Action or Radiation of the Soul . . . [the idea's] Form and Qualifications are renewed and perfected, and for the future it becomes more powerful than the rest of those at the same or lesser Distances, that have not been by such second Radiations so renewed and invigorated; and besides every such Action of the Soul does create and form a new Idea at the Center, which has Impressions that are the Result of those renewed Actions: And . . . the Impressions from the one do more readily make the Impressions from the other more sensible, in the same manner as a musical String being moved, does make another String that is unison or harmonious with it, move also, and so together make the Sound the louder, or the Impression the Stronger. (p. 145)

In addition to implying that old memory traces can be strengthened, this passage suggests the phenomenon of repetition priming. Consider three nearly identical events: A_1, A_2, and A_3, and their corresponding traces, a_1, a_2, and a_3. The occurrence of A_2 activates a_1, which reciprocally influences the processing of A_2 through sympathetic resonance. But in addition, the potency of a_1 is renewed by this activation, so that a_1 can more strongly facilitate or bias the processing of subsequent repetitions, such as A_3. Notice that A_2 can strengthen a_1, and thereby prime the processing of A_3, even if its trace, a_2, is not remembered—indeed, even if a_2 was never effectively stored in the first place. Such "dissociations" between the priming effects of an event and the event's explicit recall are characteristic of certain forms of amnesia (Shimamura, 1986). In the current literature, these dissociations are routinely attributed to separate memory systems, but they also appear to be compatible with a single-store model such as Hooke's, which combines both the multiple-trace and strength theories of repetition.

Forgetting

Hooke's account of forgetting is similarly complex, and it is related directly the memory store's spherical, chronologically layered structure. Other theorists have proposed that memory is chronologically ordered (Koffka, 1935; Köhler, 1929; Murdock, Hockley, & Muter, 1977; Semon, 1919/1923), but Hooke's assumptions appear to be unique. A model by Landauer (1975) also assumes a spherical memory structure, but the diameter of Landauer's sphere is fixed and the soul (a.k.a. "homunculus") stores memories in preexisting cells that are located for this purpose by a random-walking pointer.

Amnesia displays several time-dependent characteristics that one might expect to be compatible with a chronologically organized memory. The cases most consistent with Hooke's model may be those in which the amnesic period has a sharply defined onset and offset (Treadway, McCloskey, Gordon, & Cohen, 1992), but such cases are highly unusual. In the classic amnesic syndrome exemplified by the patient H.M., old memories are preserved and new learning is impaired (Scoville & Milner, 1957). However, such anterograde amnesia can be explained by damage to an encoding or consolidation mechanism (Squire, 1992), so it does not imply a chronological structure.

More relevant is retrograde amnesia (RA), which is often temporally ordered in the sense that recent memories are more susceptible to loss than older memories are. The time period affected can be highly variable, and the period of RA often shrinks, with older memories being recovered earlier than more recent memories (Ribot, 1887; Russell & Nathan, 1946). It is not straightforward to explain such findings in terms of Hooke's model, despite the model's chronological structure. One problem is that the soul's radiation to and from the outer layers of the memory store must pass through the inner layers, so something that obscures access to recent memories would likely affect access to older memories also. It would be possible to suppose that traces are temporarily disabled by a process that radiates out from the soul, and that variation in the temporal extent of RA is caused by variation in the strength of this process. Such a hypothesis seems inelegant, however.

Hooke mentions at least four causes of normal forgetting. One cause is "natural Decay," which he unfortunately does not discuss further.

Another cause is the breaking of the original idea sequence by "other Ideas, not formed immediately before or after," which "intrude and thrust in themselves between, out of the order they did really succeed in, so as often to interrupt and break the Chain or Order of Insertion" (p. 144). This process resembles the one that causes the order of a sequence to become increasingly jumbled with the passage of time in Estes's (1972) perturbation model of serial recall.

A third cause of forgetting relates to what is commonly referred to as blocking:

> . . . an Impediment to this Radiation of the Soul, by the Interposition of other Ideas between the Center and the Idea sought, much after the manner as the Earth interposing between the Moon and the Sun, hinders the Sun from radiating upon the Moon. And in such case the Idea may sometimes be thought to be lost, which yet may afterwards be found again when the Obstacle is removed. (p. 144)

Because the obstacle must be interposed between the center and the target, and hence is more recent, this represents a type of retroactive interference. Given the layered structure of Hooke's memory store, however, one is prompted to ask why blocking does not occur more often than it does. An answer that Hooke might have given is that memories are opaque to the soul's radiation, and therefore cause blocking, only when they are in a state of resonance. This could help explain why word-finding failures are often accompanied by the intrusion of related words (Brown & McNeill, 1966; Reason & Lucas, 1984).

The fourth cause of forgetting discussed by Hooke is retroactive interference related directly to the target memory's distance from the center:

> Again, as in the Radiation of the Sun, . . . the Radiation of the Soul is more powerful upon Ideas at a nearer than at a further Distance; and their Reaction is also more powerful back again, and that in a duplicate proportion to their Distance reciprocal much the same with that of Light . . . And thence it is, that the Memory of things long since done is for the most part very faint . . . (pp. 144–145)

This is Hooke's statement of the inverse square law, which he had earlier derived for light, and which he applied also to the force of gravity.

If we ignore forgetting due to "natural Decay," and take the inverse square of Equation 1 (which gives the memory's distance from the center), we arrive at the forgetting function:

$$\text{strength} = c \cdot \text{lag}^{-2/3}, \qquad (2)$$

in which c is a constant.

The function described by Equation 2 is shown in Figure 3. It displays the classic shape of forgetting curves, with a rapid decline near the beginning and a much slower decline later on. This should not be surprising, because Equation 2 is a power function, which is known to provide a good fit to retention data (e.g., Wixted & Ebbesen, 1992). It is remarkable that this function can be derived on a rational basis from a model that was stated 200 years before Ebbinghaus (1885) obtained data appropriate for its testing. It should be noted that Ebbinghaus did not fit his data with a power function, and it seems unlikely that he knew about Hooke's model.

Unfortunately, the exponent of Equation 2 is not a free parameter, and with rare exceptions, an exponent much lower than .67 is required for fitting human retention data. The lower the exponent, the more bowed the function becomes—that is, the greater is the slope of the function over short intervals relative to its slope over longer intervals. In the case of Ebbinghaus's data, the best-fitting exponent is about .126 (Anderson & Schooler, 1991).

Of course the independent variable in Equation 2 is not time per se, but "lag," or number of interpolated ideas. Hooke makes it clear that few ideas will be stored during sleep, so when one is asleep there should be little forgetting. The well-known results of Jenkins and Dallenbach (1924) are consistent with this prediction. Ebbinghaus's forgetting curve could have been distorted in the

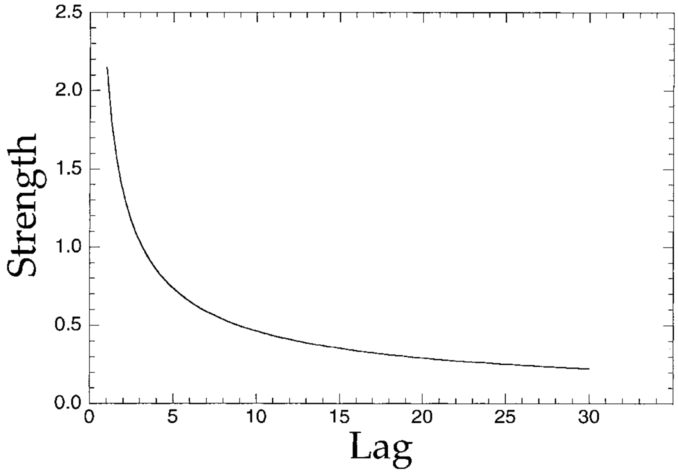

Figure 3. The forgetting function described by Equation 2.

direction of a low exponent, because he did not sleep during the shortest three of his seven retention intervals. One can take this factor into account by reducing each of the four long intervals by 1/3 (8 h per day), but this raises the best-fitting exponent to only .135, which still leaves a large discrepancy with Hooke's model.

My derivation of Equation 2 is based directly on Hooke's explicit explanation of why old memories grow faint, but it seems obvious that "natural Decay" would also be a factor. Unfortunately, Hooke gives no hint of how one would integrate decay into the forgetting equation. The standard assumption of exponential decay would likely distort the curve away from a power law, in the direction of an exponential function.

The severe constraints on Equations 1 and 2, and their resulting falsifiability, arise from Hooke's use of distance in the three-dimensional structure of the brain to affect certain computations. This may be the model's most unusual feature, but it is reminiscent of attempts to relate laws of behavior and perception directly to the topology of the cerebral cortex. To Pavlov (1927), waves of excitation and inhibition traveling over the cortex determined the laws of classical conditioning. To Köhler (1929), force fields on the cortex determined the Gestalt laws of perceptual organization. Modern neuroscience offers little support for any of these hypotheses.

Discussion

Hooke read his lecture on memory to the Royal Society on June 21 and again on June 28, 1682. The main point of discussion raised by Hooke's audience seems to have been whether he was proposing a mechanistic explanation of the soul, which Hooke denied (Singer, 1979).[8] When the posthumous lectures appeared in print in 1705, Hooke's editor, Richard Waller, gave memory prominent billing on the title page (see Figure 1), even though the lecture itself—an obvious digression from the previous topic of light—made up less than 2% of the volume. It seems likely that the book was printed in relatively small numbers, and in post-Newtonian science, the lecture collection as a whole must have appeared outdated. The rekindling of interest in Hooke's work by historians of science has had several effects, the book's publication in facsimile edition being one of them (Hooke, 1969). As I indicated earlier, however, Hooke's memory lecture has virtually escaped notice in psychology. Even early memory theorists such as Hartley (1749/1834) seem to have been unaware of Hooke's model.[9]

Moreover, as was pointed out by Singer (1979), the model bears little similarity to memory theories that had been proposed previously. Hooke approached memory not as a philosopher, but as a scientist and inventor, attempting to conceptualize a mechanistic system that would exhibit the properties of human memory. In doing so, he took positions on a number of issues that have been stressed also by later memory theorists. With the hindsight of over 300 years, how can we characterize Hooke's model?

First, Hooke viewed memories as compact and localized—not distributed, as in a holographic storage system. Each tiny trace is a physical record of an individual episode or event, and the memory store holds a very large number of such episodic traces. Memory traces are temporally organized, in two ways: Successive traces are linked by contiguity in an associative chain, and they are spherically organized in layers that reflect their relative ages or recencies. Because memory is episodic, repetition produces multiple traces; however, it also strengthens old ones. A memory trace may have multiple attributes. The exact contents of a newly formed trace depend not only on sensory information, but also on attention, resonance from previously stored traces, and more abstract forms of mental activity that occur at the time of encoding. Although abstract processing can produce memories that may be described as generic, they are nevertheless stored in the same system as are memories for specific episodes. Memory traces are activated globally, or in parallel, each resonating according to its match with ongoing mental processing. A limited-capacity attention can then be focused on an individual trace, either to recall its contents or to use distance from the center of the memory store to estimate the remembered event's recency. Although decay is also a factor, forgetting is primarily a matter of retroactive interference, attributable to the number of events interpolated between encoding and retrieval. Together with Hooke's explicit statement of the inverse square law, the geometry of the model leads to a power-law retention function.[10]

Hooke's model bears several striking similarities to the theory of Richard Semon (1919/1923; Schacter, 2001; Schacter et al., 1978). Both Hooke and Semon assumed that memories are physical, although Semon took a more distributed view than Hooke did of memory storage. For both Hooke and Semon, memories represent individual events or episodes, but Hooke emphasized the role of attention and top-down processing in shaping what is recorded in memory. This emphasis is universally accepted today, but it is relatively recent (consider, e.g., Underwood's [1963] distinction between the nominal and the functional stimulus, and Tulving's [1983] principle of encoding specificity).

Both Hooke and Semon proposed multiple-trace models of repetition, although Hooke additionally assumed that repetition could renew or strengthen older traces. Both Hooke and Semon proposed systems in which fast parallel, content-addressable retrieval is accomplished through the resonance of traces with current processing activity. In both theories as well, resonating traces can influence ongoing processing, potentially accounting for perceptual learning and repetition priming. Both Hooke and Semon discussed the role of resonance in abstraction, although abstraction was largely an intentional process for Hooke and an automatic process for Semon.

Both Hooke and Semon assumed that memory traces are chronologically ordered. Hooke tied chronological layering to a hypothesis about the physical substrate of memory. Semon on the other hand cautioned that chronological ordering was to be understood functionally, not literally. A major gap in Semon's theory, pointed out by Schacter et al. (1978), is its failure to explain forgetting. Although he also mentioned other factors, Hooke proposed what is essentially a retroactive interference theory of forgetting.

Both theorists' approaches stand in contrast to the kind of associative-strength theories that dominated thinking about learning and memory historically. Recent discussions of animal learning have emphasized this distinction as a fundamental one, by contrasting theories based on *association* and *computation* (see Leslie, 2001). In an association theory, an animal's experiences directly affect its behavioral dispositions. In a computation theory, a complex record of experiences is stored in memory and information can later be extracted from this database flexibly, as needed. Human episodic memory is computational in this sense, because behavioral criteria can be defined for the experimental subject after learning is complete, and a large number of different recall, discrimination, and judgment tasks can be performed on the basis of the same record of experience.

How can one account for the similarities between the models of Hooke and Semon? I have been unable to find evidence that Semon was familiar with Hooke's published lecture, although this is of course possible. It seems more likely that the similarities derive from the two theorists' pursuit of similar goals and use of the same kind of evidence. Hooke, of course, had no objective data to use in either developing or testing his model. No one at the time seems to have even conceived of an objective experiment on memory. Some experimental data were available to Semon, but they seem to have played no role in the development of his theory, which he explicitly based on introspection and anecdotal observation. Thus an indirect link between the two theorists may be that the evidence they used was derived from phenomenology or introspection.

Phenomenology reveals only the conscious aspects of memory and suggests especially that memory is about individual events or episodes. Subjectively, remembering seems like a partial re-creation of the original experience, with the added sense that it happened in the past. Memories generally seem to lie dormant, but to be triggered "like a bell ringing," by stimuli or thoughts that share properties with the original experience. Repeated events are not experienced identically, because they occur at different points in time and because repetition itself is an aspect of experience that can be remembered.

By contrast, in the associative tradition of Locke, Berkeley, Hume, and others, powerful variables that affect memory do so by strengthening and weakening associations. These were the processes that Ebbinghaus (1885) set out to investigate objectively, laying the foundation for the next 75 years of research on human learning and memory. Early introspective studies of memory (e.g., Strong, 1913) lacked a coherent theoretical rationale. Only in the separate Gestalt tradition did a program of objective memory research develop that was supported by phenomenological observations like those that appear to have influenced Hooke and Semon. For example, in the theories of Koffka (1935) and Köhler (1929), the contents of memory were assumed to be traces of experiences, to be spatially and temporally organized, and to reflect the memorizer's attitude at the time of encoding. Access to a trace was assumed to depend on reinstatement of the encoding conditions.

Many of the insights of Gestalt psychology were easily absorbed into the "cognitive revolution" of the 1960s (see Murray, 1995). Notably, although modern cognitive psychology insists on objective data, it fosters theories that integrate phenomenology with the computer metaphor. In a similar manner, both Semon and Hooke tried to describe information processing systems that would explain the subjective qualities of memory. Aspects of Hooke's career, discussed earlier, suggest that he possessed unusual powers of visualization. These were applied in describing a three-dimensional device that would store a running record of ideas, locate them without lengthy search according their contents, exhibit forgetting, and infer the passage of time. These still seem like appropriate goals for a model of human memory.

The foregoing may help explain why the aspects of Hooke's lecture that seem most out of date are concerned not with the psychology of memory per se, but with the physics of light (the idea that the resistance encountered by a light ray might be felt at the ray's source), and with the brain's structure and function (the assumption that tiny memory records are constantly being jostled from one location to another). It is not hard to imagine Hooke's model—stripped of such anachronisms, packaged in less archaic language, and having gone through a couple of rounds of peer review—published in a psychology journal at some time during the latter half of the 20th century.

The most jarring conflict with present-day views may be Hooke's assumption that attention, encoding, and retrieval are directed by an immaterial soul. At the very end of his lecture, Hooke capitalizes on the soul's spiritual nature, speculating that it might be able to radiate its power even outside the body, thus accounting for paranormal phenomena such as extrasensory perception. Modern cognitive psychology firmly rejects immaterial souls and paranormal phenomena. Otherwise, however, we seem to have done little more than relabel the soul with euphemisms such as "homunculus" and "central executive," and to have progressed little beyond Hooke in understanding the highest level aspects of cognition.

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NOTES

1. Singer's paper is cited briefly in Murray (1983).
2. For evidence supporting Hooke's position, see Lohne (1960).
3. Unless otherwise indicated, all page references are to Hooke (1705/1969).
4. Dyson (1997) interprets Hooke's memory store as shaped like a spiral spring, but the repeated use of the words "sphere" and "orb" imply that Hooke viewed memory as three-dimensional.
5. Hooke seems to have believed that the sensory nerves conduct light and sound directly into the brain. This misses the principle of sensory transduction. He did believe, however, that sound and light both consist

of vibrations. Hooke is also vague about the physical nature of memory storage. Some passages suggest that memory is based on structural change, whereas others seem to implicate ongoing, active vibrations.

6. A syllogism consists of a major premise (e.g., no birds are insects), a minor premise (all eagles are birds), and a conclusion (no eagles are insects) (see Adams, 1984).

7. This misattribution is also noted by Singer (1979).

8. The accusation was not trivial. Thirty years earlier, Thomas Hobbes (1651) argued that the intellect had a mechanistic basis. The House of Commons later blamed Hobbes's heresy as the likely cause of the plague, as well as the great fire of London. In 1683—the year following Hooke's lecture—the University of Oxford placed Hobbes's work on a list of books to be burned (Dyson, 1997).

9. Collier (1950) notes that Hooke's contributions to the concept of the sensory threshold were similarly ignored.

10. In this conceptualization, retroactive interference is not influenced by similarity, and there is no proactive interference. However, both effects might be derived from competition among resonating traces for attention.

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