**Memory and Optogenetic Intervention: Separating the Engram from the Ecphory**

**Abstract**

*Optogenetics* is a new intervention technique that makes it possible to control the activity of neurons with light. In this paper, I explore how the development of this experimental tool has brought about methodological and theoretical advances in the neurobiological study of memory. I begin with Semon’s (1921) distinction between the *engram* and the *ecphory*, explaining how Semon’s account of these concepts illustrates a methodological challenge for distinguishing the two. Optogenetics provides a way to intervene into the engram without the ecphory that, in turn, opens up new means for testing theories of memory error. I focus on a series of experiments from the Tonegawa research group, where optogenetic intervention is used to study false memory and forgetting.

**1. Introduction**

Optogenetics has ushered in a new era of potent and targeted control over multiple aspects of neural function. (Guru et al. 2015, 1).

Such proclamations of the promise of optogenetics are rife in contemporary neuroscience. *Optogenetics* is a new intervention technique that makes it possible to control the activity of neurons with light. Its impact on the field belies its age; the tool has only been available for little more than a decade. Within five years of the first study demonstrating its use, optogenetics was declared Method of the Year (*Science* 2010) and Breakthrough of the Decade (*Nature Methods* 2010). It’s inventor, Karl Deisseroth, was profiled in the *New Yorker* (Colapinto 2015). Optogenetics has been used to aid inquiry into an impressive array of neural systems, from addiction to zebrafish. Given the hoopla, it is unsurprising that optogenetics has captured the interest of philosophers of neuroscience as well. To many, it looks to be a scientific revolution occurring in real time, exemplifying the importance of experimental tools and novel intervention techniques for achievement in science (Bickle 2016, Craver forthcoming).

Does optogenetics really have such potential? One way to make progress on this question is to look at how the availability of this intervention technique has influenced a particular domain of inquiry. Such is the aim of this paper. I focus on the study of memory in cellular and molecular neuroscience. Memory serves as an interesting case study because it is a capacity for which the basic neural processes have long been understood. And yet, the arrival of optogenetics has brought about significant methodological and theoretical advances in just a few short years. At least in the realm of memory science, optogenetics appears to be living up to the hype.

I begin with a review of the two theoretical posits that German biologist Richard Semon (1921) introduced into the scientific study of memory—the *engram* and the *ecphory*—and the methodological challenge their entanglement presents. The neurobiological study of memory is governed by the search for the *engram*: the neural mechanism of memory storage. Complete explanation of the engram is forestalled, however, by its interconnection with the *ecphory*, the process by which engrams are reactivated in remembering. The only way to access the engram is via the ecphory. I then introduce optogenetics and show how its application to engram theory provides a solution to this basic methodological puzzle. This technique offers a way to intervene into the engram directly, circumventing the standard route through the ecphory. With the direct access that optogenetics provides, neuroscientists can not only active the engram, they can manipulate it too. This opens up new means for testing theories of memory error. I focus on two experimental techniques from an extended research project based in the Tonegawa Laboratory at the Massachusetts Institute of Technology (<http://tonegawalab.org/>), where optogenetic intervention is used to study the neural circuits involved in false memory and forgetting. In each case, optogenetic intervention has led to surprising discoveries that challenge the standard view of these memory errors.

**2. Engram Theory**

*Engram* is a new word for an old idea. It is the current scientific term for the memory trace, an idea as old as thinking about memory itself. In conversation with Theatetus, Socrates likened the mind to a block of wax into which memories are impressed. These impressions are what make possible the retention of information, ideas, and experiences over time; they are the memory traces. The comparison to wax tablets may no longer be illuminating, but the supposition that memory involves an enduring psychological and/or physical change to the rememberer, continues (Robins forthcoming).

Semon (1921) coined the term *engram* in the early 20th century, refashioning the age-old memory trace as the neurological mechanism by which information is encoded, stored, and retrieved. While much of Semon’s work has been neglected, the engram persists as the central concept guiding the investigation of memory in cellular and molecular neuroscience. Scientists working in this area often explicitly frame their research in terms of *engram theory*. Here is one such articulation of the guiding principle: “When a memory is formed, a subpopulation of neurons will be excited and stay excited latently for the storage of the memory information (engram)” (Liu, Ramirez, and Tonegawa 2014, 1).

As the quotation makes clear, the central supposition of engram theory is that engrams exist.[[1]](#footnote-1) There is some change to the brain, as the result of experience, by which the retention of information, ideas, and experiences is made possible. This shared commitment leaves plenty of room for debate and discovery. It alone does not settle the question of what kind of neural mechanism the engram is. Some may even see the above articulation of the theory’s central claim as going too far, in that it characterizes the engram in terms of neural excitation. Perhaps, instead, engrams are encoded via phase coding of oscillatory patterns over the entire hippocampal formation (Hasselmo 2012). And philosophers of neuroscience continue to disagree as to the conclusions about the nature of explanation that can be gleaned from the search for and discovery of these neural mechanisms (e.g., Theurer 2013). Nonetheless, the neurobiological study of memory remains the study of engrams. The central project is to locate these engrams, identifying the mechanism(s) by which they are formed, retained, and retrieved.

**3. The Methodological Challenge to Engram Theory**

Understanding the methodological challenge for engram theory requires a return to the theoretical background from which the concept emerged. When theorizing about the nature of memory, Semon introduced *two* theoretical posits: the engram and the ecphory. The engram is the neural memory trace; the ecphory is the process by which that trace is reactivated to produce remembering. The two are complementary and equally important for successful remembering. Of course remembering requires the retention of information, but this alone is not sufficient. In addition, remembering requires the activation of the ecphoric retrieval process by which the dormant information is revived. Semon emphasized this point by insisting on two laws of memory, one corresponding to each component:

Law of Engraphy: All simultaneous excitations within an organism form a coherent simultaneous excitation-complex which acts engraphically; that is, it leaves behind it a connected engram-complex, constituting a coherent unity.

Law of Ecphory**:** The partial recurrence of the energetic condition, which had previously acted engraphically, acts ecphorically on a simultaneous engram-complex. Or, more precisely described: the partial recurrence of the excitation-complex, acts ecphorically on the latter, whether the recurrence be in the form of original or mnemic excitations. (Semon 1921, 148)

Many of the details of Semon’s work have failed to stand the test of time. His account of the ecphory, however, and its entanglement with the engram are well vindicated by contemporary views of retrieval amongst memory scientists.[[2]](#footnote-2) Retrieval is not a neutral intervention that can be used to probe the engram without disturbance. Instead, the ecphoric process acts on the engram so that the resultant memory is a reflection of both what was stored and how it was retrieved.

The focus of the neurobiological study of memory, as the name *engram theory* reflects, is on the engram. But Semon’s work reminds us that, when studying the engram, it is critical to keep the ecphory in mind—–both as a process in its own right and as a mitigating factor in our ability to access and understand the engram. Returning to Semon’s original account of the engram promotes attention to the ecphory as well. And as we pause to consider the ecphoric process, and its deep interconnection with the engram, the more aware we become of how difficult it is to disentangle the influence of the engram and the ecphory in the act of remembering. This is the methodological challenge for engram theory.

While the distinction between the engram and the ecphory is clear in principle, the two are difficult to disentangle in practice. This is because our only insight into the contents of memory comes from the act of remembering. We determine what has been stored in memory by investigating what can be retrieved. Outside of retrieval, there is no way of establishing memory’s contents. In other words, access to the engram is only possible *via the ecphory*. How can we distinguish the information that is stored (the engram) from the process by which it is retrieved (the ecphory)? Without the ability to intervene into the engram directly, our understanding of this basic mechanism of memory storage remains limited.

In cases of successful remembering, where an accurate representation of the past experience is produced, the concern is minimal and can easily go unnoticed. But in cases of memory error, where we want to determine which factors contributed to the error and how, the methodological impasse becomes clearer. Memory errors can be sorted into two general types: errors of *commission* and errors of *omission*. Commission errors are false memories; instances where something purporting to be a memory is produced but some feature of what is produced is wrong or inaccurate. Omission errors are forgetting errors. On these occasions, one attempts to remember but is unable to call the desired information or experience to mind.

Consider a case of false memory. Suppose you are reminiscing about a past dinner party and recall your uncle telling many funny jokes during the meal—only later to learn that while the dinner did features many jokes, they were not told by your uncle as he was not there. How does such an error occur? The problem could be with the engram. You could have encoded the event incorrectly or the information may have degraded over time. But the problem could also be with the ecphory; the retrieval process may have altered or distorted the otherwise well-preserved and accurate engram. A similar problem arises for forgetting errors. Suppose a friend asks you about this dinner party and your mind goes blank. You have forgotten. The failure to produce a memory could occur because the engram has been lost, or because the ecphoric process is damaged so that it can no longer activate the engram. If the only way to access and examine the engram is by activating the ecphoric process of retrieval, then there is no way to sort between these alternatives.

In the next section, I introduce optogenetics, an intervention technique that offers a way around this general methodological puzzle. Using optogenetics to separate the engram from the ecphory provides insight into the mechanisms of false memory and forgetting.

**3. Optogenetics and Engram Theory**

Optogenetics is an intervention technique by which living cells, particularly neurons, become light responsive.[[3]](#footnote-3) *Opsins*, light-sensitive proteins, make this possible. Neuroscientists genetically engineer model organisms (mice, rabbits, fruit flies, nematodes, etc.) so that they possess a transgene that expresses a particular opsin. This transgene is then introduced into a particular type of neuron, so that the selected cells will become light responsive when the transgene is activated and the opsin is expressed. There are many different kinds of opsins. Some respond to yellow light, others to blue or red. Some opsins excite the cell; others inhibit. By shining colored light onto cells directly, via an optical fiber implant, neuroscientists can intervene to activate or inhibit specific cells. There are many reasons to be excited about optogenetics: it allows intervention into living systems, rather than inert tissue. The response to light application is instantaneous, making interventions temporally precise. Optogenetics is especially exciting for the neurobiological study of memory, I suggest, because it offers a way to intervene into the engram directly, circumventing the ecphory. In this way, it provides a novel workaround for the methodological challenge that plagues engram theory.

To illustrate this point, I discuss a series of findings from the Tonegawa Laboratory, which uses optogenetics to identify, activate, and manipulate engrams. The opsin used in these studies is Channelrhodopsin-2 (ChR2), a membrane protein found in algae. Mice are engineered to possess the ChR2 transgene, which has been introduced exclusively into neurons in the mouse’s hippocampus that are known to be involved in engram formation. This means that the light-responsive ChR2 protein will be expressed whenever hippocampal neurons with this transgene are activated. The mice used in these studies are also engineered to be sensitive to doxycycline (*dox*), an antibiotic given through the animal’s water supply. The mice will only express the transgene when they are *not* exposed to the antiobiotic. This allows experimenters to control when light-sensitive proteins are produced. The mice are given *dox* steadily at all times except for the experimental condition, so that the only hippocampal neurons with light-responsive properties will be those that were active during the experiment. In the studies discussed below, the experimental condition involves exploration of a conditioning chamber that is novel to the mouse. The neurons active during this exploration encode the mouse’s experience of the environment—they constitute the engram for this spatial memory.[[4]](#footnote-4) The engram neurons alone are light responsive. To reactivate the engram, the researchers do not need to instigate retrieval, which for mice would mean returning them to the original conditioning chamber. They can bypass the ecphory and proceed directly to the engram by simply turning on a light.

Overcoming this basic methodological challenge is, in and of itself, an exciting breakthrough. Its impact on engram theory, and the neurobiological study of memory more broadly, becomes clearer once this basic technique is used to explore the influence of further manipulations of the engram and how they contribute to memory error. Doing so provides novel insight into our understanding of both false memory and forgetting errors, as I illustrate in the two case studies below.

*Case Study 1: False Memory*

False memories are memory errors of commission, inaccurate representations of past experiences that the rememberer herself takes to be genuine memories—like the example of the uncle at the dinner party from Section 3. Decades of research in cognitive psychology reveal that such false memories are produced surprisingly easily and often. Memory scientists want to explain these errors, and when doing so, face the methodological challenge. Are false memories the result of a missing engram or a distorting ecphory? Most memory theorists who seek to explain false memories favor the former answer. They endorse *Constructivism*, according to which memory relies on a general network of information rather than memory traces or engrams. The process of remembering, on this view, is making use of ecphoric resources—information available and of interest at the time of retrieval—to produce a plausible representation of a past experience (De Brigard 2014a; Michaelian 2016).

Theorizing about false memory has not been constrained by evidence about the underlying neural mechanisms because there has been no such evidence. False memory is a human phenomenon; evidence has been restricted to that which is available with the methods of cognitive psychology and cognitive neuroscience. Without the ability to translate these methods to studies of non-human animals, using the methods of cellular and molecular neuroscience, there has been little hope of ever discovering such a mechanism. That is, until recently. Using optogenetic intervention to create and manipulate engrams, the Tonegawa research group has been able to create and manipulate engrams so as to produce false memories in mice.

In Ramirez et al. (2013), mice form a false memory for a context they have previously encountered, remembering it as fearful even though their initial experience with the context did not include any fearful stimuli. The study begins with the creation of light-responsive engrams, using the procedure described at the beginning of Section 3. While removed from *dox*, genetically modified mice are each given a novel conditioning chamber to explore, forming the engram. Each mouse is then dosed with *dox*, preventing the formation of any new engrams and taken to a second novel conditioning chamber. Once in the second chamber, the optical implant is turned on, reactivating the engram from the original chamber. While this light-responsive engram is active, the mouse is given a set of foot shocks, instilling a fear memory. This results in a set of mice that each have a light-responsive engram with spatial information about one conditioning chamber and information about a fearful encounter in a second conditioning chamber.

Mice with this manipulated engram are then exposed to one of three test conditions. Some are returned to the original chamber, others are returned to the second chamber, and still others are taken to a third novel conditioning chamber. When returned to the second chamber—where they received foot shocks initially—mice respond by freezing, a characteristic fear response. Interestingly, mice returned to the original chamber also display this fear response, freezing in place even though they did not receive foot shocks in this chamber. Mice taken to a novel chamber behave differently—they explore the novel environment, suggesting against the idea that the manipulated engrams have made the animals generally fearful.

In a second study (Redondo et al. 2014), the Tonegawa research group reproduced this result with more elaborate memories, demonstrating the ability to produce false memories where the emotional response is reversed. Using the same basic method to create and manipulate engrams, the group added valence to the initial engram: when mice were introduced to the first conditioning chamber, their exploration was paired with either a positive stimulus (exposure to a female mouse) or a negative stimulus (foot shocks). Next, for a set of these mice, reactivation of the light-responsive engram in the second chamber was paired with a stimulus of the opposite valence. Mice who previously received foot shocks were exposed to a female mouse, and vice versa. When later returned to the original chamber the mice display behavior reflective of their experience in the second chamber—i.e., mice that received foot shocks in the first chamber display exploratory, pleasure-seeking behavior and mice that were exposed to a female display a freezing fear response. Their behavior contradicts their experience in the chamber, indicating a reversal of the original engram’s valence.

These studies offer examples of distorted, false memories in mice. The mice returned to the original chamber exhibit this most clearly. These mice respond to the environment as familiar or remembered, but behave in a way that fails to reflect their previous experience in this context. The information they have retained is distorted and inaccurate. The Ramirez et al. (2013) and Redondo et al. (2014) studies provide the first examples of false memories in non-human animals. The Tonegawa research group interprets their findings accordingly, making an explicit connection between these results and studies of false memories in cognitive psychology (Ramirez et al. 290).

This breakthrough in the understanding of the mechanism of false memory is made possible by optogenetic intervention. By allowing for the direct excitation and then manipulation of an engram, researchers could explore possible changes to the engram that occur without influence from the ecphory. In this way, the results from the Tonegawa research group provide the beginning sketches of a mechanism for false memory formation. This initial sketch is enough to shake up theoretical explanations of false memory. The results challenge Constructivism, which explains false memory by denying the existence of traces.[[5]](#footnote-5) They show, instead, false memories as the result of manipulating, but retaining traces. In this way, they suggest an alternative theoretical approach to false memory, one that retains an engram.

*Case Study 2: Consolidation*

Forgetting is a familiar and frustrating memory error. It is the failure to retrieve or recall information that was previously learned or acquired. As introduced in Section 3, attempts to explain forgetting raise a question complicated by the methodological blend of the engram and ecphory. In cases of forgetting, we want to know whether the error is due to a failure of the engram or a failure of the ecphory. Is the information unavailable or merely unaccessible (Tulving and Pearlstone 1966)? Because the engram can only be investigated via the ecphory, this question is difficult to answer directly.

Progress on this question is also complicated by the fact that forgetting is hard to study experimentally, as it is difficult to predict when it will occur. One of the best avenues for studying forgetting is consolidation. *Consolidation* is the process by which information moves from temporary to long-term memory storage. If the consolidation process is disrupted, forgetting results. The neural mechanisms of consolidation have been studied for more than a century and are well understood (McGaugh 2000). Put simply: learning involves changes to the interactions between neurons. Transitioning from learning to long-term memory storage requires making these structural alterations permanent. Consolidation is the process by which this occurs. The synthesis of proteins stabilizes the synaptic connections between neurons. If there is interference into the consolidation process—by administration of a protein synthesis inhibitor, for example—then the result is forgetting.

The way in which consolidation is defined and investigated presupposes an answer to the methodological question above. The *consolidation hypothesis* just is the claim that the engram moves, gradually, from an initial, fragile state to a more stable form (McGaugh 2000). Researchers who study consolidation simply assume that forgetting, at least in the case of failure to consolidate, is the result of damage to the engram rather than damage to the ecphory.

Recently, the Tonegawa research group has applied optogenetic methods to the study of consolidation-based forgetting. As with the studies of false memory discussed above, the Ryan et al. (2015) paper begins with the creation of light-responsive engrams in genetically modified mice. In this study, these engrams are created for mice who are introduced to a novel conditioning chamber where they receive foot shocks. Immediately following the encounter, half of the mice are given anisomycin (ANI), a protein synthesis inhibitor, and the other half are given saline solution as a control. Following on previous studies of consolidation interference, the expectation is that this manipulation will prevent the mice given ANI from remembering the foot shocks when they are later returned to the chamber, but the mice given only the sham intervention of saline will remember and respond accordingly (i.e., freeze when returned to the chamber). And this is what Ryan et al. found. At both 1 and 3 days after the initial encounter in the conditioning chamber, the mice given saline froze when they were returned while the mice given ANI did not. By disrupting consolidation, the exposure to ANI appears to have induced forgetting in one set of mice.

Returning the mouse to the original conditioning chamber activates retrieval; it provides access to the engram ecphorically. Since the engram involved in the foot shock conditioning is light responsive, Ryan et al. (2015) were able to conduct a second set of experiments exploring the effect of activating the engram directly via optogenetic intervention. These experiments began in the same way as the first consolidation study: mice formed a light responsive engram for the experience of receiving foot shocks in a conditioning chamber and then half of the mice were given ANI and half were given saline. One day after this intervention, the mice were tested in the environment to ensure consolidation disruption (i.e., forgetting) in the mice that received ANI. The next day (two days after the initial training), each mouse was placed in a distinct chamber and the foot shock engram was activated via the mouse’s optical implant. In this condition, all mice—those who had received ANI and those who had received saline—displayed the characteristic fear response. Ryan and colleagues performed several variations of this experiment, testing for the effect of activating distinct portions of the engram optogenetically. For each manipulation, the result was the same. There was no significant difference between the recall behavior for mice whose consolidation had been disrupted and for those whose consolidation had not. By activating the engram directly, the researchers were able to reinstate the memory; or, optogenetic intervention allowed them to undo the forgetting caused by disruption to the consolidation process. The ability to recover the memory of the foot shock experience onptogenetically persisted for 8 days following the original training session.

These results provide a novel answer to the methodological question posed above, one that challenges standard assumptions about consolidation. Forgetting, the failure to retrieve information, could be the result of engram decay or ecphoric failure. At least in the case of consolidation failure, memory scientists have supposed that forgetting is due to loss of the engram. But when non-consolidated engrams are activated directly, as optogenetic intervention makes possible, remembering is successful. This suggests that the deficit in these cases of forgetting is due to the ecphory instead. As Susumu Tonegawa explained in an interview about this study, “The majority of researchers have favored the storage theory, but we have shown in this paper that this majority theory is probably wrong” (Knight 2015). Forgetting, at least in the case of failure to consolidate, is an ecphoric deficit, not an engraphic one.

**5. Conclusion**

Many neuroscientists and philosophers of neuroscience are excited by the potential for optogenetics to revolutionize our understanding of the neural mechanisms underlying a host of behaviors and processes. The application of optogenetic techniques to the neurobiological study of memory illustrates how such revolution occurs. The ability to activate the engram directly, as optogenetic intervention allows, makes it possible to separate the engram from the ecphory. Previously, the conceptual distinction between these components of memory was difficult to reflect in experimental practice.

By manipulating the engram to produce false memories in Ramirez et al. (2013) and Rendondo et al. (2014) and to repair forgetting in Ryan et al. (2015), the Tonegawa research group has demonstrated how optogenetic techniques can be used to gain new insight into the neural mechanism(s) responsible for memory errors. Even from these initial studies, optogenetic intervention produces findings that challenge the received view of each of these errors. Many memory scientists have assumed that false memories are the result of a failure to retain memory traces, but the Ramirez et al. and Redondo et al. studies demonstrate the production of false memory via retained, distorted engrams. Similarly, memory theorists have long supposed that disrupting the consolidation process produces forgetting by erasing the original engram. Ryan et al. shows that traces are not erased during consolidation; they merely become inaccessible.

The use of optogenetics to explore the neural mechanisms of memory is still in its early days. It is too early, even, to know whether the results discussed in this paper can be successfully replicated and extended. What is clear, however, is that the arrival of this experimental tool has re-energized the neurobiological study of memory, by providing the previously impossible means for separating the engram from the ecphory.

**References**

Bickle, John. 2016. “Revolutions in neuroscience: Tool development.” *Frontiers in Systems*

*Neuroscience*, doi: 10.3399/fnsys.2016.00024

Colapinto, John. 2015. “Lighting the Brain: Karl Deisseroth and the optogenetics

breakthrough.” *The New Yorker,* May 18 2015.

Craver, Carl F. Forthcoming. “Thinking about Interventions: optogenetics and makers

knowledge of the brain.” In *Causation in Biology and Philosophy*, ed. Kenneth Waters. Minneapolis: University of Minnesota Press.

De Brigard, Felipe. 2014a. “Is Memory for Remembering? Recollection as a form of episodic

hypothetical thinking.” *Synthese* 191: 155–185.

De Brigard, Felipe. 2014b. “The Nature of Memory Traces.” *Philosophy Compass* 9: 402–414.

Deisseroth, Karl. 2011. “Optogenetics.” *Nature Methods* 8: 26–29.

Guru, Aakash, Ryan J. Post, Yi-Yun Ho, and Melissa R. Warden. 2015. “Making Sense of

Optogenetics.” *International Journal of Neuropsychopharmacology* 18: 1–8.

Hasselmo, Michael E. 2012. *How We Remember: Brain Mechanisms of Episodic Memory*.

Cambridge, MA: MIT Press.

Knight, Helen. 2015. “Researchers Find ‘Lost’ Memories.” *MIT News,* May 28 2015.

McGaugh, James L. 2000. “Memory – A Centruy of Consolidation.” *Science* 287: 248–251.

Michaelian, Kourken. 2016. *Mental Time Travel: Episodic memory and our knowledge of the*

*personal past.* Cambridge, MA: MIT Press.

Ramirez, Steve, Xu Liu, Pei-Ann Lin, Junghyup Suh, Michele Pignatelli, Roger Redondo,

Tomás Ryan, and Susumu Tonegawa. 2013. “Creating a False Memory in the Hippocampus.” *Science* 341: 388–391.

Redondo, Roger L., Joshua Kim, Autumn Arons, Steve Ramirez, Xu Liu, and Susumu

Tonegawa. 2014. “Bidirectional Switch of the Valence Associated with a Hippocampal

Contextual Memory Engram.” *Nature* 513: 426–430.

Robins, Sarah K. Forthcoming. “Memory Traces.” In *Routledge Handbook of Philosophy of*

*Memory*, ed. Sven Bernecker and Kourken Michaelian. New York: Routledge.

Robins, Sarah K. 2016. “Optogenetics and the Mechanism of False Memory.” *Synthese* 193:

1561–1583.

Ryan, Tomás J., Dheeraj S. Roy, Michele Pignatelli, Autumn Arons, and Susumu Tonegawa.

2015. “Engram Cells Retain Memory under Retrograde Amnesia. *Science* 348: 1007–1013.

Schacter, Daniel. 2001. *Forgotten Ideas, Neglected Pioneers: Richard Semon and the story of*

*memory*. Ann Arbor, MI: Sheridan Books.

Semon, R. (1921). *The Mneme*. London: George Allen & Unwin.

Theurer, Kari. 2013. “Compositional Explanatory Relations and Mechanistic Reduction.”

*Minds and Machines* 23: 287–307.

Tulving, Endel and Zena Pearlstone. 1966. “Availability versus Accessibility of Information

in Memory for Words,” *Journal of Verbal Learning and Verbal Behavior* 5: 381–391.

1. It is an interesting to ask whether, in the neuroscience of memory, commitment to the existence of discrete memory traces is a pretheoretical commitment or empirical discovery. For a discussion of this issue, see De Brigard (2014b). [↑](#footnote-ref-1)
2. For a defense of Semon’s work on this point, see Schacter (2001). [↑](#footnote-ref-2)
3. Deisseroth (2011) provides a thorough overview of optogenetic techniques. [↑](#footnote-ref-3)
4. In an early paper, the Tonegawa group demonstrated the ability to produce and reactivate light-responsive engrams in mice (Liu et al. 2012). Given space limitations, I focus my discussion of experimental detail on the subsequent studies of engram manipulation. [↑](#footnote-ref-4)
5. For an extended argument in defense of this claim, see Robins (2016). [↑](#footnote-ref-5)