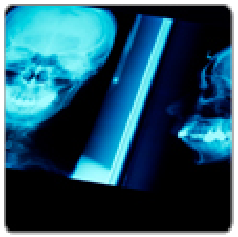

Semantic Memory

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Introduction

Semantic memory refers to our general world knowledge that encompasses memory for concepts, facts, and the meanings of words and other symbolic units that constitute formal communication systems such as language or math. In the classic hierarchical view of memory, declarative memory was subdivided into two independent modules: episodic memory, which is our autobiographical store of individual events, and semantic memory, which is our general store of abstracted knowledge. However, more recent theoretical accounts have greatly reduced the independence of these two memory systems, and episodic memory is typically viewed as a gateway to semantic memory accessed through the process of abstraction. Modern accounts view semantic memory as deeply rooted in sensorimotor experience, abstracted across many episodic memories to highlight the stable characteristics and mute the idiosyncratic ones. A great deal of research in neuroscience has focused on both how the brain creates semantic memories and what brain regions share the responsibility for storage and retrieval of semantic knowledge. These include many classic experiments that studied the behavior of individuals with brain damage and various types of semantic disorders but also more modern studies that employ neuroimaging techniques to study how the brain creates and stores semantic memories. Classically, semantic memory had been treated as a miscellaneous area of study for anything in declarative memory that was not clearly within the realm of episodic memory, and formal models of meaning in memory did not advance at the pace of models of episodic memory. However, recent developments in neural networks and corpus-based tools for modeling text have greatly increased the sophistication of models of semantic memory. There now exist several good computational accounts to explain how humans transform first-order experience with the world into deep semantic representations and how these representations are retrieved and used in meaning-based behavioral tasks. The purpose of this article is to provide the reader with the more salient publications, reviews, and themes of major advances in the various subfields of semantic memory over the past forty-five years. For more in-depth coverage, we refer the reader to the manuscripts in the General Overviews section.

General Overviews

While semantic memory has been the subject of a considerable amount of research, the topic has not garnered enough attention to warrant any full volumes being written on the topic. Nevertheless, there are numerous overviews of semantic memory that exist as part of more general volumes. Chang 1986 provides an early account of the field of semantic memory. Binder and Desai 2011, Thompson-Schill 2003, and Yee, et al. 2013 provide overviews of neurologically based accounts of semantic memory. Finally, Balota and Coane 2008, McRae and Jones 2013, and Yee, et al. 2017 provide an in-depth overview of the study of semantic memory and incorporate the history of the field, experimental evidence, and computational models of semantic memory.

Balota, D. A., and J. H. Coane. 2008. Semantic memory. In *Handbook of learning and memory: A comprehensive reference*. Edited by J. H. Byrne, H. Eichenbaum, R. Menzel, H. L. Roediger III, and D. Sweatt, 512–531. Amsterdam: Elsevier.

Summarizes findings from various approaches to the study of semantic memory.

Binder, J. R., and R. H. Desai. 2011. The neurobiology of semantic memory. *Trends in Cognitive Sciences* 15.11: 527–536.

Provides a summary of the role of varied brain regions implicated in semantic processing.

Chang, T. M. 1986. Semantic memory: Facts and models. *Psychological Bulletin* 99.2: 199.

Reconsiders the extent and richness of semantic memory, reestablishing early findings in the field.

McRae, K., and M. N. Jones. 2013. Semantic memory. In *The Oxford handbook of cognitive psychology*. Edited by D. Reisberg, 206–216. New York: Oxford Univ. Press.

Summarizes the literature in experimental studies and computational models of semantic memory.

Thompson-Schill, S. L. 2003. Neuroimaging studies of semantic memory: Inferring 'how' from 'where.' *Neuropsychologia* 4.3: 280–292.

Reviews the locations of activations for semantic representations, discussing functional neuroimaging studies in semantic memory.

Yee, E., E. G. Chrysikou, and S. L. Thompson-Schill. 2013. Semantic memory. In *The Oxford handbook of cognitive neuroscience: Core topics*. Vol. 1. Edited by Kevin Ochsner and Stephen Kosslyn, 353–374. Oxford: Oxford Univ. Press.

This article reviews literature that supports the grounding of semantic models in sensorimotor inputs.

Yee, E., M. N. Jones, and K. McRae. 2017. Semantic memory. In *The Stevens' handbook of experimental psychology and cognitive neuroscience*. 4th ed. Edited by J. Wixted and S. Thompson-Schill, 319–356. Chichester, UK: Wiley.

Provides a comprehensive review of semantic memory, summarizing computational modeling and experimental data.

Journals

Semantic memory has been broadly discussed across the major experimental and theoretical journals of psychological science. It is not a topic that has a single journal dedicated to it. Hence, many significant contributions to the field of semantic memory can be found distributed across the major theoretical journals of cognitive psychology and cognitive science. However, such journals also cover a wide range of other theoretical topics. This section includes the particular journals that tend to contain the greatest concentration of experimental and modeling work pertaining to semantic memory. The *Journal of Memory and Language* focuses on semantic memory from the perspective of language comprehension. *Journal of Experimental Psychology: Learning, Memory, and Cognition* and *Memory & Cognition* focus on cognitive processes involved in semantic memory. *Language, Cognition, and Neuroscience* emphasize the neurological underpinnings of semantic memory. Finally, *Discourse Processes* looks at semantic memory ranging from a single word meaning up to larger, compositional topics.

***Discourse Processes*. 1977–.**

Publishes experimental studies of discourse in sociology, psychology, and other disciplines. While other journals are more focused on learning, comprehension, and representation of single-word meaning, this journal focuses on larger units of meaning that involve combining individual concepts.

***Journal of Experimental Psychology: Learning, Memory, and Cognition*. 1975–.**

Publishes experimental research on basic processes of cognition, learning, memory, imagery, concept formation, problem solving, decision making, thinking, reading, and language processing.

***Journal of Memory and Language*. 1962–.**

Emphasizes psycholinguistic theory and contains experimental work related to semantic memory and language comprehension. JML is a continuation of the *Journal of Verbal Learning and Verbal Behavior* (JVLVB). The journal was renamed *JML* in 1985 but has been published as JVLVB since 1962.

***Language, Cognition, and Neuroscience*. 1985–.**

Publishes interdisciplinary research that studies language and its neural bases. It differs from the abovementioned journals in that the focus is on neural structures and processes that give rise to semantic phenomena. LCN is a continuation of *Language and Cognitive Processes* (1985–2013), renamed in 2014.

***Memory & Cognition*. 1973–.**

Publishes research on human memory and learning, along with other related cognitive processes, including decision making, problem solving, cognitive development, and mathematical and computer models of cognition. The journal is a publication of the Psychonomic Society.

Classic Modular Taxonomy

Semantic memory was first introduced by Tulving 1972 as a means to differentiate between general knowledge and specific event knowledge. Tulving 1983 further explores the distinction between semantic and episodic memory. While the perspective has changed with regard to whether semantic memory is a separate system from episodic memory, early behavioral and neurological evidence pointed toward a clear separation between the systems. For instance, case study evidence from Milner, et al. 1968 and Cohen and Squire 1980 demonstrates how learning impairments differentially affect the development of semantic and episodic memories in amnesiac patients. Additionally, Squire 1987 and Squire 1992 provide neurological evidence of distinct memory systems. Allport 1985, Warrington and McCarthy 1983, and Warrington and Shallice 1984 present case studies demonstrating localized deficits in semantic memory.

Allport, D. A. 1985. Distributed memory, modular subsystems and dysphasia. In *Current perspectives in dysphasia*. Edited by S. K. Newman and R. Epstein, 207–244. Edinburgh, UK: Churchill Livingstone.

Discusses semantic representations in terms of discrete systems as a means of addressing particular deficiencies observed in dysphasic individuals. Posits that sensorimotor systems are the means through which internal representations of the world are made and maintained in the brain.

Cohen, N. J., and L. R. Squire. 1980. Preserved learning and retention of pattern-analyzing skill in amnesia: Dissociation of knowing how and knowing that. *Science* 210.4466: 207–210.

Demonstrates that amnesiacs who are unable to develop new semantic memories are able to develop procedural skills, demonstrating a distinction between declarative and non-declarative forms of memory.

Milner, B., S. Corkin, and H. L. Teuber. 1968. Further analysis of the hippocampal amnesic syndrome: 14-year follow-up study of HM. *Neuropsychologia* 6.3: 215–234.

Follows up on famous amnesiac, H. M. Though unable to develop new semantic memories, he was able to learn maze solving and other motor skills at a slow rate. This case study served as initial evidence suggesting the distinction of systems between declarative knowledge (episodic and semantic) and implicit procedural memory.

Squire, L. R. 1987. *Memory and brain*. New York: Oxford Univ. Press.

Discusses neurobiological underpinnings that create the early framework for the discussion of memory processes.

Squire, L. 1992. Declarative and nondeclarative memory: Multiple brain systems supporting learning and memory. *Journal of Cognitive Neuroscience* 4.3: 232–243.

Builds a theory of multiple brain systems involved in declarative and non-declarative memory based on combining evidence from various neurological studies including lesion studies.

Tulving, E. 1972. Episodic and semantic memory. In *Organization of memory*. Edited by E. Tulving and W. Donaldson, 382–403. New York: Academic Press.

Proposes the initial taxonomy that differentiated semantic from episodic memory. Explores the potential usefulness of the delineation, setting the course for memory study for the next thirty years.

Tulving, E. 1983. *Elements of episodic memory*. Oxford: Clarendon Press.

Discusses the interplay between semantic information and episodic traces in memory.

Warrington, E. K., and R. McCarthy. 1983. Category specific access dysphasia. *Brain* 106.4: 859–878.

Presents a case study of an individual, V. E. R., with reduced verbal comprehension skills due to damage to the left hemisphere. V. E. R. demonstrates particular deficits inability to group particular semantic categories accurately.

Warrington, E. K., and T. Shallice. 1984. Category specific semantic impairments. *Brain* 107.3: 829–853.

Presents a series of case studies in dysphasic patients. Discusses inconsistent identification of particular categories between subjects that contrast with earlier findings relating to categorization.

Conceptual Organization

Over the course of semantic memory research, many distinctions have been discussed to articulate the processes and representations of concepts. Here we present the most salient distinctions in the literature.

Prototypes and Exemplars in Semantic Memory

Whereas the other sections under Conceptual Organization deal with the types of information stored, the distinction between prototypes and exemplars is a theoretical debate over how concepts are stored in semantic memory. Prototypes represent the central tendency within a category of concepts. The theory of prototypes emerges from early research by Posner and Keele 1968 demonstrating that the most typical instances of a category are more easily categorized than less typical instances within the same category. Prototype theory was articulated and more extensively explored by Rosch and Mervis 1975 and Rosch, et al. 1976 with the notion of cognitive economy. Categorical deficits identified by Warrington and McCarthy 1987 in dysphasic individuals support a prototype theory. The competing view of exemplars more resembles episodic memory. Exemplars are experiences that are stored in memory without abstraction, and retrieval from exemplar-based memory entails an operation over all the stored exemplars. Exemplar theory typically accompanies an argument that episodic and semantic memory are not exclusive processes. An exemplar account of concept memory is proposed by Medin and Schaffer 1978 and further explored by Smith and Medin 1981. Murphy 2004 provides a historical overview of the theories and discusses the distinction between the two memory process models. Prototype models posit an accumulation of information with loss. The prototype becomes the stored representation, which leads to the difficulty of prototypes to account for outliers of a category. An exemplar account of memory posits an accumulation without loss, and categories emerge as a result of the retrieval process. A challenge for exemplar theory is accounting for the large amount of information that needs to be stored.

Medin, D. L., and M. M. Schaffer. 1978. Context theory of classification learning. *Psychological Review* 85.3: 207–238.

Argues against models of abstraction by proposing an exemplar-based explanation of memory, here called "context theory of classification." Contrasts context theories versus prototype theories and demonstrates that an exemplar explanation better accounts for behavioral data.

Murphy, G. 2004. *The big book of concepts*. Cambridge, MA: MIT Press.

Provides a thorough account of the development of prototype and exemplar theories and the experimental data that led to the development of the theories.

Posner, M. I., and S. W. Keele. 1968. On the genesis of abstract ideas. *Journal of Experimental Psychology* 77.3: 353–363.

Establishes that a prototype is more easily categorized than other patterns also within the category. As variability between category items increased, general categorization performance with highly distorted instances also increased. Argues for some abstraction process based on experience with instances.

Rosch, E., and C. B. Mervis. 1975. Family resemblances: Studies in the internal structure of categories. *Cognitive Psychology* 7.4: 573–605.

Evaluates the definition of a category prototype in terms of shared attributes within category, unshared attributes between categories, and cue validity. Posits that family resemblance between members of a category better accounts for behavior than a list of criterial features.

Rosch, E., C. B. Mervis, W. D. Gray, D. M. Johnson, and P. Boyes-Braem. 1976. Basic objects in natural categories. *Cognitive Psychology* 8.3: 382–439.

Argues that basic categorizations of concrete objects are determined by differentiating between the most salient cues. Discusses the tendency of subjects to refer to objects at their most generalized, prototypical level.

Smith, E. E., and D. L. Medin. 1981. *Categories and concepts*. Vol. 9. Cambridge, MA: Harvard Univ. Press.

Introduces competitor theory exemplar models to offer a different explanation of semantic memory to prototype models.

Warrington, E. K., and R. A. McCarthy. 1987. Categories of knowledge: Further fractionations and an attempted integration. *Brain* 110.5: 1273–1296.

Analyzes category deficits in an individual with global dysphasia. Introduces a model that can account for apparently categorical deficits in memory based on the association of the function of sensory inputs. Suggests semantic structure is based on categorical structures, which are based on differential associations between sensory inputs.

Concrete and Abstract Concepts

Differentiating between concrete and abstract concepts represents a distinction between the referent values of those concepts. Concrete concepts refer to things that are experienced in the real world. They are things that have a strong mapping to sensorimotor phenomena. Abstract concepts have a weak mapping to sensorimotor experience. Dual coding theory suggests that linguistic concepts are encoded and processed at two levels. At the concrete level, a person experiences seeing, touching, and perhaps smelling a tree. At the abstract level, a person knows that a tree is a plant with leaves that perform photosynthesis. Dual coding theory had been first suggested in the 1970s, and early research from Schwanenflugel and Shoben 1983 does not support the theory. However, Paivio 1990 and Paivio 1991 articulate the evidence in support of dual coding theory. Kousta, et al. 2011 and Recchia and Jones 2012 demonstrate that concrete and abstract words are processed differently. On the other hand, Pecher, et al. 2011 demonstrates how abstract concepts emerge from sensorimotor experience. Moreover, Barsalou and Wiemer-Hastings 2005 theorizes neural mechanisms that derive abstract concepts from concrete concepts. Most recently, Binder 2016 argues in favor of a learning mechanism that can derive abstract concepts from concrete experiences.

Barsalou, L. W., and K. Wiemer-Hastings. 2005. Situating abstract concepts. In *Grounding cognition: The role of perception and action in memory, language, and thought*. Edited by D. Pecher and R. A. Zwaan, 129–163. New York: Cambridge Univ. Press.

Implements perceptual simulation theory focusing in particular on applying it to abstract concepts.

Binder, J. R. 2016. In defense of abstract conceptual representations. *Psychonomic Bulletin & Review* 23.4: 1096–1108.

Reviews of neuropsychological research in support for “convergence zones” that serve to integrate related stimuli regardless of modality. Argues for an abstract concept representation that relates concepts separately from any specific modality, while allowing for a concept acquisition mechanism that is based in concrete experiences.

Kousta, S. T., G. Vigliocco, D. P. Vinson, M. Andrews, and E. Del Campo. 2011. The representation of abstract words: Why emotion matters. *Journal of Experimental Psychology: General* 140.1: 14–34.

Presents experimental data demonstrating disparate lexical decision latencies to abstract words, creating an observable behavioral distinction between abstract and concrete words.

Paivio, A. 1990. *Mental representations: A dual coding approach*. Oxford: Oxford Univ. Press.

Proposes the dual coding theory of semantic processing, where information is stored at two levels—perceptually and linguistically. When perceptual information is lacking when processing abstract ideas, linguistic information provides the semantic basis of processing.

Paivio, A. 1991. Dual coding theory: Retrospect and current status. *Canadian Journal of Psychology* 45.3: 255–287.

Reviews and evaluates literature relating to dual coding theory. Responds to early criticisms of dual coding theory. Available online by subscription.

Pecher, D., I. Boot, and S. Van Dantzig. 2011. Abstract concepts: Sensory-motor grounding, conceptual metaphors, and beyond. In *The psychology of learning and motivation*. Vol. 54. Edited by B. Ross, 217–248. Burlington, VT: Academic Press.

Evaluates the effectiveness of theories within the realm of grounded cognition to account for abstract concepts. Argues for the need of situational context in addition to image schemas in order to fully account for abstract concept representation.

Recchia, G., and M. N. Jones. 2012. The semantic richness of abstract concepts. *Frontiers in Human Neuroscience* 6:315.

Distinguished between abstract and concrete concepts by evaluating the properties of concepts, including the number of features, the contextual dispersion, and the number of semantic neighbors between concepts. Demonstrated that the processing of concepts generally is aided by number of features, while the processing of abstract concepts relies more heavily on a linguistic framework.

Schwanenflugel, P. J., and E. J. Shoben. 1983. Differential context effects in the comprehension of abstract and concrete verbal materials. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 9:82–102.

Evaluates competing predictions between a dual coding theory and a context availability theory. Tests the predictions in verbal processing tasks, overall supporting a context availability model.

Thematic Relations and Event Knowledge

Thematic relationships emerge from knowledge about events. Thematic relationships extend from knowledge about events, where everything involved in an event experience develops relationships in semantic memory. Moss, et al. 1995 demonstrates that semantic memory is influenced by event knowledge, and Estes, et al. 2011 defines thematic relationships between concepts as those concepts that play complementary roles in an event. For instance, consider a visit to the doctor versus a visit to the dentist. These events share many general relationships: appointment, waiting room, health service professionals. However, the specific relationships between concepts involved in each respective event represent unique thematic relationships: doctor, nurse, stethoscope; dentist, hygienist, dental floss. McRae, et al. 1998 and McRae, et al. 2005 explore the relationship between event knowledge and sentence comprehension, showing that comprehension is immediate and dependent on expectancies drawn from prior knowledge, respectively. Chwilla and Kolk 2005 and Hare, et al. 2009 explore the breadth of thematic relationships using priming tasks. Khalkhali, et al. 2012 argues for the importance of temporal sequence on the processing of thematic relationships, demonstrating a lack of priming in the absence of correct order.

Chwilla, D. J., and H. H. Kolk. 2005. Accessing world knowledge: Evidence from N400 and reaction time priming. *Cognitive Brain Research* 25.3: 589–606.

Tests the effect of thematic relations on speed of processing. When two-word stimuli were presented simultaneously, participants were able to “rapidly integrate” the information to construct a larger context, priming some third word that bound the two stimuli together.

Estes, Z., S. Golonka, and L. L. Jones. 2011. Thematic thinking: The apprehension and consequences of thematic relations. In *Psychology of learning and motivation*. Edited by B. Ross, 249–294. Vol. 54. Burlington, VT: Academic Press.

Defines thematic relationships as things that perform complementary roles rather than exchangeable roles. Argues that thematic relationships serve an important cognitive role in the development of categories.

Hare, M., M. N. Jones, C. Thomson, S. Kelly, and K. McRae. 2009. Activating event knowledge. *Cognition* 111.2: 151–167.

Extends understanding of different associations where priming occurs and does not occur. For instance, event-related nouns prime nouns involved with the event, while location-related nouns prime nouns that typically are found at those locations. Instrument nouns primed the things upon which they are used but not the people who use them.

Khalkhali, S., J. Wammes, and K. McRae. 2012. Integrating words that refer to typical sequences of events. *Canadian Journal of Experimental Psychology* 66.2: 106–114.

Posits that temporally based event information is encoded in memory by demonstrating that words in correct temporal sequence showed priming effects, whereas out of sequence stimuli did not. Available online by subscription.

McRae, K., M. Hare, J. L. Elman, and T. Ferretti. 2005. A basis for generating expectancies for verbs from nouns. *Memory and Cognition* 33.7: 1174–1184.

Considered whether humans predict upcoming words based on expectancies drawn from knowledge of event-based verb usage. Results indicate that thematic relationships between agents, and the roles played by particular agents play a large role in sentence comprehension.

McRae, K., M. J. Spivey-Knowlton, and M. K. Tanenhaus. 1998. Modeling the influence of thematic fit (and other constraints) in on-line sentence comprehension. *Journal of Memory and Language* 38.3: 283–312.

Explored the effect of thematic fit on sentence comprehension via computational modeling. Demonstrated that thematic relationships are evaluated immediately at the level of sentence comprehension, rather than evaluated post-hoc.

Moss, H. E., R. K. Ostrin, L. K. Tyler, and W. D. Marslen-Wilson. 1995. Accessing different types of lexical semantic information: Evidence from priming. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 21.4: 863–883.

Shows that relationships between concepts may be event based. Identifies priming effects that emerge from semantic categories and semantic relationships based on functionality, such as instrument relations (e.g., broom-floor) and script relations (e.g., restaurant-wine). Priming patterns depended on modality. Available online by subscription.

Semantic and Associative Relations

This section digs into the types of similarity that exists between words. The distinction between semantic and associative relationships between words provides a general context to understand word relatedness. Words with semantic relations share similarity between their meanings. For instance, the animals “bear” and “fox” are more semantically related than “bear” and “rocket ship.” Alternatively, associative relationships are words that typically occur together. For instance, “bear” and “honey” are not semantically similar, but they typically occur in similar contexts and are therefore associated. Given distributional definition of words (see Distributional Models), words that appear in similar contexts have similar meanings. Therefore, words with semantic relationships will always have associated relationships, but words with strong association do not necessarily have semantic relationships. Nelson, et al. 2000 quantifies the strength of association between words by asking participants to perform a free association task. An early review of the literature, Lucas 2000, appeared to support the distinction between semantic and associative relatedness in that semantic relationships produced priming while associative relationships did not. However, Hutchison 2003 showed that both forms of relatedness could yield priming. While such a distinction between semantic and associative relationships may be a useful tool for the theorist, Brainerd, et al. 2008 argues that the two forms of relatedness are not discrete but rather rely on each other. McRae, et al. 2012 furthers the argument against a strong semantic-associative distinction.

Brainerd, C. J., Y. Yang, V. F. Reyna, M. L. Howe, and B. A. Mills. 2008. Semantic processing in ‘associative’ false memory. *Psychonomic Bulletin & Review* 15.6: 1035–1053.

Argues that it may not be useful to differentiate between associative and semantic relatedness, because semantic relatedness provides a context to understand word associations. Available online by subscription.

Hutchison, K. A. 2003. Is semantic priming due to association strength or feature overlap? A microanalytic review. *Psychonomic Bulletin & Review* 10.4: 785–813.

In contrast with Lucas 2000, argues that both semantic and associative relationships produce priming.

Lucas, M. 2000. Semantic priming without association: A meta-analytic review. *Psychonomic Bulletin & Review* 7.4: 618–630.

Meta-analysis that concludes that semantic priming can occur in the absence of word-association relatedness, and priming in conjunction with word association relatedness, but not with pure word-association priming.

McRae, K., S. Khalkhali, and M. Hare. 2012. Semantic and associative relations: Examining a tenuous dichotomy. In *The adolescent brain: Learning, reasoning, and decision making*. Edited by V. F. Reyna, S. Chapman, M. Dougherty, and J. Confrey, 39–66. Washington, DC: AP.

Proposes a less strictly defined line between associative and semantic relatedness, where associated memories are construed by an individual as being semantically significant.

Nelson, D. L., C. L. McEvoy, and S. Dennis. 2000. What is free association and what does it measure? *Memory and Cognition* 28:887–899.

Uses a free association task to evaluate the strength of relationships between words, as well as to model the set of strongest associates for a given word. Free association data is widely used as a standard for model performance.

Semantic Memory Tasks and Data Sources

When selecting stimuli for semantic memory experiments, or evaluating the performance of computational models, researchers typically use large databases of human behavior in semantic memory or rating tasks. Included in this section are papers summarizing some of the more commonly employed tasks and databases. These papers take different forms. Some present tasks exclusively, some present databases of task data, and others provide extensive composite databases. Some of these papers such as Roediger and McDermott 1995 offer lists of words that are likely to produce false recall in a recall task. Mitchell and Lapata 2010 has a language task that reveals aspects of language compositionality. Nelson, et al. 2004 provides a database summarizing free association data. Hutchison, et al. 2013 presents an extensive database on lexical decision data. Hill, et al. 2016 presents a database on associative data. Miller 1995 provides a database of tagged language. Maki, et al. 2004 presents a database with numerous semantic measures and introduces a new summary measure of semantic relatedness.

Hill, F., R. Reichart, and A. Korhonen. 2016. Simlex-999: Evaluating semantic models with (genuine) similarity estimation. *Computational Linguistics* 4:665–695.

Presents a data set that controls for similarity based on association, such that associated words that are dissimilar receive low ratings. Data set is available for research purposes. Available online by subscription.

Hutchison, K. A., D. A. Balota, J. H. Neely, et al. 2013. The semantic priming project. *Behavior Research Methods* 45.4: 1099–1114.

Offers a large database of normed lexical decision data. Discusses structure of data and user interface. Offers data set freely for analysis. Available online by subscription.

Maki, W. S., L. N. McKinley, and A. G. Thompson. 2004. Semantic distance norms computed from an electronic dictionary (WordNet). *Behavior Research Methods, Instruments, & Computers* 36.3: 421–431.

Gives an extensive data set incorporating numerous semantic relatedness measures. Introduces another measure to approximate relatedness between words without human behavioral data. Data set is available for research purposes. Available online by subscription.

Miller, G. A. 1995. WordNet: A lexical database for English. *Communications of the ACM* 38.11: 39–41.

Brief presentation of large database of tagged language. Pairs of words are tagged based on various forms of polysemous relationships they hold. Database is available for research purposes. Available online by subscription.

Mitchell, J., and M. Lapata. 2010. Composition in distributional models of semantics. *Cognitive Science* 34.8: 1388–1429.

Discusses combinatorial effect of language that results in meaning beyond the mere words used: that is, compositionality. Presents language task to gather information regarding compositionality in language. Available online.

Nelson, D. L., C. L. McEvoy, and T. A. Schreiber. 2004. The University of South Florida free association, rhyme, and word fragment norms. *Behavior Research Methods, Instruments, & Computers* 36.3: 402–407.

Presents an extensive database of free association data. Explains structure of data for general use by a researcher. Available online by subscription.

Roediger, H. L., and K. B. McDermott. 1995. Creating false memories: Remembering words not presented in lists. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 21.4: 803–814.

Expands on previous work in illusory memories. Presents a set of lists that were effective in producing high rates of false recall in participants. Available online by subscription.

Semantic Priming

Priming is the most widely used behavioral task to study the structure of semantic memory. Meyer and Schvaneveldt 1971 first proposed a novel paradigm to identify relationships between words. In a priming task, the participant makes a speeded response, typically a two-alternative decision (word/nonword, category judgment, etc.) to a single target word. The target word is preceded by a brief presentation of a prime word. If a related prime word speeds processing of the target word (e.g., *dog-cat*) relative to an unrelated prime (*metal-cat*), it is considered to have facilitated the processing of the target because the two have some shared information in their mental representations. Semantic priming has been widely used to explore how word meanings are related to each other, giving important clues about the learning mechanisms used to construct semantic memory. Neely 1991 and McNamara 2005 provide reviews of priming literature. McKoon and Ratcliff 1992 and Chwilla and Kolk 2002 argue alternatively against and for a spreading activation account of semantic priming, respectively. Balota and Paul 1996 and Hutchison, et al. 2008 discuss findings that had a strong impact on the field of semantic priming in general.

Balota, D. A., and S. T. Paul. 1996. Summation of activation: Evidence from multiple primes that converge and diverge within semantic memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 22.4: 827–845.

Presents an experiment that evaluates the effect of using multiple primes for a given target. Available online by subscription.

Chwilla, D. J., and H. H. Kolk. 2002. Three-step priming in lexical decision. *Memory and Cognition* 30.2: 217–225.

Demonstrates mediated priming effects that cannot be explained be word co-occurrence but can be explained by semantic spreading activation.

Hutchison, K. A., D. A. Balota, M. J. Cortese, and J. M. Watson. 2008. Predicting semantic priming at the item level. *The Quarterly Journal of Experimental Psychology* 61.7: 1036–1066.

Discusses particular semantic priming phenomena. Particularly, the effect of priming can be predicted by item, order, and semantic relatedness. Suggests caution when comparing semantic priming results from different prime-target sets. Available online by subscription.

McKoon, G., and R. Ratcliff. 1992. Spreading activation versus compound cue accounts of priming: Mediated priming revisited. *Journal of Experimental Psychology: Learning, Memory, and Cognition* 18.6: 1155–1172.

Argues against spreading activation account of semantic priming. Provides experimental phenomena suggesting that priming phenomena result from words frequently sharing time in a semantic memory buffer during encoding.

McNamara, T. P. 2005. *Semantic priming: Perspectives from memory and word recognition*. New York: Psychology Press.

Reviews literature on semantic priming, models used to explain priming, and particular priming phenomena.

Meyer, D. E., and R. W. Schvaneveldt. 1971. Facilitation in recognizing pairs of words: Evidence of a dependence between retrieval operations. *Journal of Experimental Psychology* 90.2: 227–234.

Introduces a novel paradigm of study. Presents data from word recognition task distinguishing words from non-words. Notes emergent effect when words were associated versus unassociated. Discusses potential explanations for effect. Available online by subscription.

Neely, J. H. 1991. Semantic priming effects in visual word recognition: A selective review of current findings and theories. In *Basic processes in reading: Visual word recognition*. Edited by D. Besner, and G. W. Humphreys, 264–336. Hillsdale, NJ: Lawrence Erlbaum Associates.

Early review of literature related to semantic priming and models used account for the relevant data.

Neurobiology of Semantic Memory

The study of semantic memory through neurobiological research takes two avenues: neural deficits and neural imaging. Each avenue yields a particular form of information. Neural deficit research is the study of behavioral deficiencies resulting from damage or degenerative disorders. Such research emphasizes the localization of brain regions necessary for a particular function. Neural imaging research allows us to see what regions are recruited when certain forms of semantic processing are taking place. Imaging allows for the observation of the distribution of processing across the cortex.

Evidence from Brain Damage and Memory Disorders

The study of brain damage and memory disorders yields specific information regarding the role of particular brain regions in semantic processing. Deficits that emerge from localized damage or degeneration demonstrate dedicated functionality of that brain region to a particular form of semantic processing. For instance, the role of the temporal lobe and the hippocampus in memory was identified by Scoville and Milner 1957 by studying patients with lesions to those brain regions. It is important to consider the pathology of the damage or disorder, as its source determines how culpable a particular brain region may be for particular functionality. For instance, a brain lesion from a surgical procedure may result in different behavioral deficits than one resulting from a stroke or head trauma. Warrington 1975 and Caramazza and Shelton 1998 studied patients with localized brain lesions, arguing for the emergence of categorization skills from particular brain regions. O'Kane, et al. 2004 used the famous lesion subject H. M. to demonstrate a facilitative rather than executive role in the hippocampus for new memory formation. Advancing degenerative disorders have also been used to implicate brain regions in semantic processing. For instance, Hodges, et al. 1992 identified the temporal lobe in the representation of semantic categories and grammatical structures. It is important to keep in mind that certain functionality may be subsumed by other parts of the brain, and other avenues of research must be considered to have a full picture of the role of brain regions in semantic processing.

Caramazza, A., and J. R. Shelton. 1998. Domain-specific knowledge systems in the brain: The animate-inanimate distinction. *Journal of Cognitive Neuroscience* 10.1: 1–34.

Reviews literature relating to category deficits emerging from damage to particular brain regions. Disputes theory of category structure emerging from sensory systems. Argues in favor of evolutionarily based neural subsystems that serve as the structure of categories.

Hodges, J. R., K. Patterson, S. Oxbury, and E. Funnell. 1992. Semantic dementia: Progressive fluent aphasia with temporal lobe atrophy. *Brain* 115.6: 1783–1806.

Presents a set of case studies on individuals with advancing dysphasia. Tests semantic categories and grammatical structures. Demonstrates loss of semantic categories while maintaining grammatical structures, as well as motor skills and episodic memories. Reduced function of the temporal lobe is implicated.

O'Kane, G., E. A. Kensinger, and S. Corkin. 2004. Evidence for semantic learning in profound amnesia: An investigation with patient HM. *Hippocampus* 14.4: 417–425.

Continues memory research with the subject H. M. Tests H. M. on ability to identify celebrities that became famous after his surgery. Demonstrates that despite damage to hippocampus, H. M. acquired semantic memories of word meanings that came into use after the onset of his amnesia. Suggests facilitative role, rather than executive role, of hippocampus in memory. Available online by subscription.

Scoville, W. B., and B. Milner. 1957. Loss of recent memory after bilateral hippocampal lesions. *Journal of Neurology, Neurosurgery, and Psychiatry* 20.1: 11–21.

Early report of findings demonstrating the reduction of memory capabilities following lesions to the medial temporal lobe, anterior temporal lobe, and hippocampus.

Warrington, E. K. 1975. The selective impairment of semantic memory. *The Quarterly Journal of Experimental Psychology* 27.4: 635–657.

Early evidence in favor of a distinction between subordinate and superordinate category distinctions. Presents case studies of patients with different lesion damage to the brain. Demonstrates disparate semantic deficits at varying levels of abstract conceptual representations. Available online by subscription.

Evidence from Brain Imaging

Research relating brain imaging and semantic processing emphasize distributed rather than localized processing of information. In general, semantic memory increasingly considered to be a distributed, multimodal, and parallel process. Chao, et al. 1999 and Martin and Chao 2001 present evidence that processing of semantic information is distributed across the entire cortex. Binder, et al. 2009 and Huth, et al. 2012 give evidence that relates the processing of semantic memory to multiple brain regions and modalities. Clarke, et al. 2011 demonstrates that activation across the cortex increases as the conceptual complexity increases. Patterson, et al. 2007 and McNorgan, et al. 2011 argue for the integration of multiple modalities in hubs and hierarchies, respectively. Finally, Thompson-Schill, et al. 1997 and Tyler, et al. 2004 demonstrate how new evidence may change old interpretations of processes in memory.

Binder, J. R., R. H. Desai, W. W. Graves, and L. L. Conant. 2009. Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex* 19.12: 2767–2796.

Presents a meta-analysis of functional neuroimaging studies that demonstrate that particular brain regions not related to any particular modality are implicated in storing particular forms of semantic memory. Reviews converging evidence for a distributed, multi-modal account of semantic memory. Available online.

Chao, L. L., J. V. Haxby, and A. Martin. 1999. Attribute-based neural substrates in temporal cortex for perceiving and knowing about objects. *Nature Neuroscience* 2.10: 913–919.

Presents evidence that category-based organization may occur within modality-specific regions of the brain. Available online by subscription.

Clarke, A., K. I. Taylor, and L. K. Tyler. 2011. The evolution of meaning: Spatio-temporal dynamics of visual object recognition. *Journal of Cognitive Neuroscience* 23.8: 1887–1899.

Presents research demonstrating recurrent interactions between ATL and posterior temporal lobe. Explores the effect of level of complexity in semantic processing demands, demonstrating an increase in recurrent interaction between lobes corresponding to an increase in complexity of concept. Available online by subscription.

Huth, A. G., S. Nishimoto, A. T. Vu, and J. L. Gallant. 2012. A continuous semantic space describes the representation of thousands of object and action categories across the human brain. *Neuron* 76.6: 1210–1224.

Argues against a one-to-one mapping of concept to brain location for processing. Presents a novel visualization technique that portrays the distribution of activations for concepts across the cortex. Available online by subscription.

Martin, A., and L. L. Chao. 2001. Semantic memory and the brain: Structure and processes. *Current Opinion in Neurobiology* 11.2: 194–201.

Reviews literature demonstrating that concept processing is distributed across the cortex. Discusses roles of particular brain regions in the memory retrieval processes.

McNorgan, C., J. Reid, and K. McRae. 2011. Integrating conceptual knowledge within and across representational modalities. *Cognition* 118.2: 211–233.

Discusses theory of convergence zones where modality specific processes are integrated. Presents research demonstrating a hierarchical organization of convergence zones to build semantic representations. Available online by subscription.

Patterson, K., P. J. Nestor, and T. T. Rogers. 2007. Where do you know what you know? The representation of semantic knowledge in the human brain. *Nature Reviews Neuroscience* 8.12: 976–987.

Reviews hypothesis that certain regions of brain serves as amodal hubs to integrate different types of features and to extract concept representations. Available online by subscription.

Thompson-Schill, S. L., M. D'Esposito, G. K. Aguirre, and M. J. Farah. 1997. Role of left inferior prefrontal cortex in retrieval of semantic knowledge: A reevaluation. *Proceedings of the National Academy of Sciences* 94.26: 14792–14797.

Presents findings that suggest the inferior frontal gyrus is implicated in particular semantic processing by selecting between stimuli. Contrasts explanation with previous findings suggesting that IFG plays a role in retrieval.

Tyler, L. K., E. A. Stamatakis, P. Bright, et al. 2004. Processing objects at different levels of specificity. *Journal of Cognitive Neuroscience* 16.3: 351–362.

Presents an fMRI neuroimaging study that supports the idea that the anterior temporal lobe is a processing center (not just a knowledge center) for object categorization. Available online by subscription.

Semantic Development

There has been considerable debate over the development of semantic memory, with special attention being paid to infants and children. Similar to the general “nature versus nurture” debate, there is much discussion revolving around the nativist versus empiricist view of the development of concepts in children. According to the nativist perspective, humans are predisposed toward conceptualizing things in particular ways. More specifically, within the cognitive structure of a human, there is a native framework that guides the development of concepts. Gelman and Markman 1986 argues for natural categories by demonstrating how children perform categorization tasks for observable and unobservable features. Markman 1990 further argues that categorization must be constrained given the combinatorial vastness of the potential categories that could be constructed. Spelke, et al. 1992 furthers the nativist argument. Carey 2009 extensively lays out the argument and research for the nativist position. The nativist explanation emerged to account for the challenging problem of mapping words to objects. However, a contrary explanation challenges the need for such a predisposition, known as the empiricist account. Research in support of the empiricist account seeks to demonstrate that there is no need for framework or specific mechanisms for the accrual of word-referent mappings. Landau, et al. 1988 and Waxman and Markow 1995 argue that language provides the structure by which categories are formed in children. Smith and Yu 2008 shows that categories are not formed immediately but are rather a process of reducing uncertainty. See Bloom 2000 for an articulation of empiricist position. Given the support for both arguments, Sloutsky 2010 attempts to find a middle ground between the two positions. McMurray, et al. 2012 provides a review of the debate.

Bloom, P. 2000. *How children learn the meanings of words*. Vol. 377. Cambridge, MA: MIT Press.

Discusses an empiricist account of the conceptual development of children. Suggests that humans have a wide set of cognitive tools that collectively allow for the development of word meaning associations without the need for a set of predisposed category biases.

Carey, S. 2009. *The origin of concepts*. Oxford: Oxford Univ. Press.

Presents a nativist account of the development of concept in infants. Suggests that infants are predisposed toward the interpretation of sensory input according to innate biases.

Gelman, S. A., and E. M. Markman. 1986. Categories and induction in young children. *Cognition* 23.3: 183–209.

Presents research exploring the extent to which children place animals in categories based on observable versus unobservable features. Suggests that children may start with a predilection for categorizing based on natural categories and that tendencies for categorization change as the child gains experiences. Available online by subscription.

Landau, B., L. B. Smith, and S. S. Jones. 1988. The importance of shape in early lexical learning. *Cognitive Development* 3.3: 299–321.

Explores degree to which children and adults categorize based on similar features. Varies shape, size, and texture stimuli, demonstrating a developmental trend that a bias to categorize based on shape grows over the course of development. Suggests language plays a role in determining the degree to which a feature determines categorization in the development of a child. Available online by subscription.

Markman, E. M. 1990. Constraints children place on word meanings. *Cognitive Science* 14.1: 57–77.

Argues that the range of possible word-meaning associations a child can make must be constrained because of the large number of possible associations that can be made. Constraints deal with the way a child maps meaning to an object. For instance, a word is associated with a whole object, not a part of one. Reviews relevant literature. Available online by subscription.

McMurray, B., J. S. Horst, and L. K. Samuelson. 2012. Word learning emerges from the interaction of online referent selection and slow associative learning. *Psychological Review* 119.4: 831–877.

Extensively reviews literature relating to a nativist-versus-empiricist stance in concept development of children. Argues that a slow accumulation of associative knowledge accounts for the trajectory of development without the need for specialized systems of categorization. Demonstrates the efficacy of such an account with thorough computational modeling. Available online by subscription.

Sloutsky, V. M. 2010. From perceptual categories to concepts: What develops? *Cognitive Science* 34.7: 1244–1286.

Suggests an account of development to unify nativist and empiricist theories. Discusses apparent shift in conceptualization with development, where children are more likely to make categorizations based on perceptual elements and adults are more likely to make categorizations based on linguistic or other semantic elements. Reviews experimental results in support of some unified perspective of development. Available online by subscription.

Smith, L., and C. Yu. 2008. Infants rapidly learn word-referent mappings via cross-situational statistics. *Cognition* 106.3: 1558–1568.

Demonstrates that infants can resolve the uncertainty of word-meaning associations by attending to co-occurrences across multiple exposures. Argues that infants develop the association between word and meaning over the course of development, rather than resolving uncertainty immediately. Available online by subscription.

Spelke, E. S., K. Breinlinger, J. Macomber, and K. Jacobson. 1992. Origins of knowledge. *Psychological Review* 99.4: 605–632.

Discusses early experimental evidence in favor of a nativist account of concept development. Available online by subscription.

Waxman, S. R., and D. B. Markow. 1995. Words as invitations to form categories: Evidence from 12-to 13-month-old infants. *Cognitive Psychology* 29.3: 257–302.

Presents experimental evidence of the way nouns and adjectives guide the attention of an infant. Argues that words provide a structure by which infants categorize objects. Available online by subscription.

Embodied Semantics

Early theorizing separated semantic memory from episodic memory, as discussed in Classic Modular Taxonomy. Such modularity yielded conclusions that semantic memory was amodal and somehow distinct from sensory input. Over time, semantic memory became increasingly detached from grounded experience. As semantic knowledge became an increasingly abstract construct that was separate from sensorimotor experiences, evidence against the amodal theory of semantic memory began to grow. Damasio 1989, Barsalou 1999, and Vigliocco, et al. 2009 propose models demonstrating the effectiveness of semantic models derived from multiple modalities. However, studies such as Pecher, et al. 2003 and Yee, et al. 2013 show how brain activations during word processing demonstrate that processing of words occurs across the cortex in areas specifically related to sensorimotor experience. Pulvermüller 1999, Pecher and Zwaan 2005, Barsalou 2008, and Mahon and Caramazza 2008 form a series of reviews that articulate the debate surrounding embodied semantics, arguing in favor of a grounded view of semantic memory.

Barsalou, L. W. 1999. Perceptions of perceptual symbols. *Behavioral and Brain Sciences* 22.4: 637–660.

Proposes a model of semantic representation where cognitive process operate on experiential stimuli. Justifies this approach with relevant literature.

Barsalou, L. W. 2008. Grounded cognition. *Annual Review of Psychology* 59:617–645.

Articulates the argument against models of semantic memory that do not incorporate multimodal sensory input. Reviews literature supporting a grounded approach to semantic memory. Available online by subscription.

Damasio, A. R. 1989. Time-locked multiregional retroactivation: A systems-level proposal for the neural substrates of recall and recognition. *Cognition* 33.1–2: 25–62.

Presents a cognitive and neurologically based model of sensorimotor input. Discusses how statistical redundancies of features across modalities yields a complex set of relationships between concepts: more complex than could be achieved were information available via only one modality.

Mahon, B. Z., and A. Caramazza. 2008. A critical look at the embodied cognition hypothesis and a new proposal for grounding conceptual content. *Journal of Physiology-Paris* 102.1–3: 59–70.

Discusses strong forms of arguments in favor for and against embodied cognition. Suggests a synthesis of theories where abstract concepts are instigated by perceptual information. Available online by subscription.

Pecher, D., R. Zeelenberg, and L. W. Barsalou. 2003. Verifying different-modality properties for concepts produces switching costs. *Psychological Science* 14.2: 119–124.

Demonstrates that switching modalities reduces processing speeds of perceptually grounded words in the same way that processing costs occur when processing different modalities. Advocates a semantic system that incorporates perceptual systems. Available online by subscription.

Pecher, D., and R. A. Zwaan. 2005. *Grounding Cognition: The Role of Perception and Action in Memory, Language, and Thinking*. Cambridge, UK: Cambridge Univ. Press.

Comprehensively reviews grounded theory of semantics, addressing work done on sentence evaluation, emotion, sensorimotor, and abstract concept processing.

Pulvermüller, F. 1999. Words in the brain's language. *Behavioral and Brain Sciences* 22.2: 253–279.

Reviews data demonstrating words associated with a particular modality result in brain activations in regions associated with that modality. Demonstrates the distribution of semantic memory across the cortex.

Vigliocco, G., L. Meteyard, M. Andrews, and S. Kousta. 2009. Toward a theory of semantic representation. *Language and Cognition* 1.2: 219–247.

Proposes a model of semantic representation where cognitive process operate on experiential stimuli. Justifies this approach with relevant literature. Available online by subscription.

Yee, E., E. G. Chrysikou, E. Hoffman, and S. L. Thompson-Schill. 2013. Manual experience shapes object representations. *Psychological Science* 24.6: 909–919.

Presents research that demonstrates that action is not ancillary to a memory representation of objects. Shares research where performing hand motions incompatible with a frequently manipulated object interferes with a participant's ability to talk about that object, whereas such interference does not occur with unrelated objects. Available online by subscription.

Models of Semantic Memory

Computational models of semantic memory attempt to explain the cognitive processes of learning, representation, and retrieval. This is a challenging task, as the only measure of success for a given model is to compare a model output to human behavior. Nevertheless, there has been impressive success in accounting for human behavior through a computational modeling approach. Such a demonstration provides evidence that a particular algorithm is psychologically significant. There have been different approaches to modeling semantic memory over time. Classic Models incorporated early ideas of feature overlap and spreading activation. Since then, more complex models have been proposed that have explored the tradeoffs between ease of interpretation and behavior replication. Connectionist Models implement a neuron-like substrate as the representation medium. While not entirely distinct from a connectionist approach, Distributional Models intuit a word's meaning based on its context and the contexts it shares with other words.

Classic Models

There are a few key trends in the early models of semantic memory. Collins and Quillian 1969 proposed semantic networks as an early attempt to explain the trajectory of thought. In a semantic network, each node represents a concept, and edges between nodes constituted some form of relationship between concepts. When a node is retrieved or activated, the activation of the node spreads to other connected concepts. There were empirical attempts to identify relationships between words. Osgood, et al. 1957 attempted to measure the perceived similarity between words, while Rosch 1975 used empirical methods to demonstrate category behaviors between concepts. Models provide a means of exploring whether theory can produce behavior. Smith, et al. 1974 attempts to account for feature relatedness and prototypical behavior. Hintzman 1986 uses a computational model to further arguments in favor of an exemplar model of memory rather than a prototype model. While these models accounted for particular aspects of behavior, none of the representational structures were based on a learned representation: a notable deficiency for classic models of semantic representation.

Collins, A. M., and M. R. Quillian. 1969. Retrieval time from semantic memory. *Journal of Verbal Learning and Verbal Behavior* 8.2: 240–247.

Introduces the classical traversal of hierarchically organized concepts to infer semantic relatedness. Available online by subscription.

Hintzman, D. L. 1986. 'Schema abstraction' in a multiple-trace memory model. *Psychological Review* 93.4: 411–428.

Implements an episodic model of memory to semantic representation. Demonstrates that such a model can retrieve prototype information, offering model support for an episodic basis of semantic memory. Available online by subscription.

Osgood, C. E., G. J. Suci, and H. P. Tannenbaum. 1957. *The measurement of meaning*. Urbana: Univ. of Illinois Press.

Provides an early account of meaning as a multidimensional semantic space, operationalizing computational aspects thorough human ratings on semantic differential scales.

Rosch, E. 1975. Cognitive representations of semantic categories. *Journal of Experimental Psychology: General* 104.3: 192–233.

Presents numerous experiments demonstrating the boundaries of semantic categories. Explores relationship between perceptual effects and extended practice on category boundaries. Available online by subscription.

Smith, E. E., E. J. Shoben, and L. J. Rips. 1974. Structure and process in semantic memory: A featural model for semantic decisions. *Psychological Review* 81.3: 214–241.

Presents a two-stage feature model that performs categorization tasks based on defining and characteristic features. Model accounts for category-based semantic effects. Available online by subscription.

Connectionist Models

At first glance, connectionist models appear to resemble semantic networks. Knowledge is represented as a network of weighted edges between nodes. But rather than localist nodes representing words, the representation of a word's meaning is distributed across a network of nodes. Note that this is a different sort of distribution from theory underlying Distributional Models. The strength of connectionist networks emerges from the weakness of classic models – representation develops over sequential exposure to stimuli. Typical construction is to have a set of nodes composed of the input layer, some set of intervening nodes, and then an output layer of nodes. A series of papers had an enormous impact on the trajectory of research in semantic memory. Rumelhart, et al. 1986 solved the problem of training weights between nodes in a connectionist model by using back propagation, setting the stage for numerous advancements in cognitive modeling and machine learning. McClelland and Rumelhart 1985 proposes a unique method of storing a memory trace in a connectionist system. Elman 1990 introduces a computationally rigorous method of introducing time into a connectionist model using recurrent networks. Soon to follow was research demonstrating the effectiveness of connectionist networks to model behaviors and behavioral deficits. Rumelhart and Todd 1993 makes a general argument in favor of connectionist networks in cognitive modeling. Farah and McClelland 1991, Plaut and Shallice 1993, and McClelland, et al. 1995 demonstrate that behavioral deficits can be modeled using connectionist networks. Plaut and Booth 2000, Rogers and McClelland 2004, and Rogers, et al. 2004 show that the trajectories of semantic development can also be accounted for using connectionist networks.

Elman, J. L. 1990. Finding structure in time. *Cognitive Science* 14.2: 179–211.

Presents a connectionist model to produce representation that deals with time explicitly. Model performance responds to context dependencies as well as generalization in categorization. Available online by subscription.

Farah, M. J., and J. L. McClelland. 1991. A computational model of semantic memory impairment: Modality specificity and emergent category specificity. *Journal of Experimental Psychology: General* 120.4: 339.

Introduces a model that can account for apparently categorical deficits in memory based on the association of the function of sensory inputs. Available online by subscription.

McClelland, J. L., and D. E. Rumelhart. 1985. Distributed memory and the representation of general and specific information. *Journal of Experimental Psychology: General* 114.2: 159–188.

Presents the first sighting of what will become parallel distributed processing, where a given memory trace is distributed across a set of nodes with edge weights that can be updated. Available online by subscription.

McClelland, J. L., B. L. McNaughton, and R. C. O'Reilly. 1995. Why are there complementary learning systems in the hippocampus and neocortex: Insights from the successes and failures of connectionist models of learning and memory. *Psychological Review* 102:419–457.

Compares structure of connectionist models to effects of hippocampus damage. Uses principles of connectionist models to clarify disparate learning processes occurring in different brain regions.

Plaut, D. C., and J. R. Booth. 2000. Individual and developmental differences in semantic priming: Empirical and computational support for a single-mechanism account of lexical processing. *Psychological Review* 107.4: 786–823.

Reduces the phenomena relating to semantic priming to a connectionist account of memory. Analyzes the effect of age on particular priming effects. Demonstrates how the effects are accounted for within a connectionist model. Available online by subscription.

Plaut, D. C., and T. Shallice. 1993. Deep dyslexia: A case study of connectionist neuropsychology. *Cognitive Neuropsychology* 10.5: 377–500.

Evaluates previous work by Hinton and Shallice relating to the ability of connectionist networks to reproduce symptoms of deep dyslexia. Discusses properties of connectionist networks that account for the phenomenon. Available online by subscription.

Rogers, T. T., and J. L. McClelland. 2004. *Semantic cognition: A parallel distributed processing approach*. Cambridge, MA: MIT Press.

Presents a connectionist model that accounts for the trajectory of development of categorization. Studies the ability of classic Rumelhart feed-forward networks to process semantic signals. Demonstrates sensitivity of parallel distributed processing to higher order statistical regularities.

Rogers, T. T., L. Ralph, A. Matthew, et al. 2004. Structure and deterioration of semantic memory: A neuropsychological and computational investigation. *Psychological Review* 111.1: 205–235.

Presents a connectionist model that maps referent values between words and objects. Model performance accounts for human behavior relating to semantic impairments. Available online by subscription.

Rumelhart, D. E., G. E. Hinton, and R. J. Williams. 1986. Learning representations by back-propagating errors. *Nature* 323.6088: 533–536.

Proposes back propagation as a means to overcome computational limitations of early connectionist models. Statistical redundancies distributed in a text can be represented within a hidden layer of nodes with edge weights updated by back propagation. Available online by subscription.

Rumelhart, D. E., and P. M. Todd. 1993. Learning and connectionist representations. In *Attention and performance 14: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience*. Edited by D. E. Meyer and S. Kornblum, 3–30. Cambridge, MA: MIT Press.

Discusses the potential of connectionist networks to explain cognitive processes, maintaining a need for clarity in the discussion of the development of the connectionist representation of knowledge.

Distributional Models

Distributional models of semantic memory accrue semantic representations by attending to statistical regularities in the environmental context. Within this framework, a text corpus is commonly used as a proxy for statistical experience with language. Generally, distributional models reflect statistical learning mechanisms demonstrated by humans (see Smith and Yu 2008 cited under Semantic Development). The flexibility of such models allows for extensive exploration into specific learning mechanisms and representational structures. Distributional models vary in their definitions of how contextual relationships are formed. LSA treats words within an entire document as sharing context (see Landauer and Dumais 1997), while HAL defines a context as a limited window of words (see Lund and Burgess 1996). Learning algorithms vary. For instance Pennington, et al. 2014 proposes GLOVE, which tallies word by word matrix, making it necessary that an entire corpus be scanned before semantic vectors are derived. Alternatively, Kwantes 2005, Jones and Mewhort 2007, and Howard, et al. 2011 propose episodic learning systems where semantic vectors are accumulative and updated over the course of training. Mikolov, et al. 2013 uses a connectionist model to extract word similarities from the statistical structure of a corpus. Rather than focusing on word similarities, Griffiths, et al. 2007 uses Bayesian modeling to predict topics discussed in a given document. Bullinaria and Levy 2007 discusses some of the methods of extracting distributional data from a corpus, arguing that simple statistics can yield robust behavioral modeling. Turney and Pantel 2010 provides a review of distributional models. Despite the success of such models, a salient argument against this approach is that information is solely text based and does not account for the multimodal sensory experience that occurs in the semantic development experienced by humans.

Bullinaria, J. A., and J. P. Levy. 2007. Extracting semantic representations from word co-occurrence statistics: A computational study. *Behavior Research Methods* 39.3: 510–526.

Examines computational approach to extracting semantic information from higher order distributional statistics. Demonstrates that simple statistical procedures can produce results that robustly account for behavioral data. Available online by subscription.

Griffiths, T. L., M. Steyvers, and J. B. Tenenbaum. 2007. Topics in semantic representation. *Psychological Review* 114.2: 211–244.

Implements a Bayesian approach to probabilistically model the compositional information within a sentence or document. Model performance accurately replicates word association data, specifically asymmetrical responses in human behavior. Describes how such a model could scale up to account for more diverse sets of semantic information. Available online by subscription.

Howard, M. W., K. H. Shankar, and U.K. Jagadisan. 2011. Constructing semantic representations from a gradually changing representation of temporal context. *Topics in Cognitive Science* 3.1: 48–73.

Co-opts a model used in the study of episodic memory, the temporal context model. Models error-predictive hippocampal learning to predict performance on word association task. Suggests model as a means of integrating semantic memory into a broader account of declarative memory. Available online by subscription.

Jones, M. N., and D. J. K. Mewhort. 2007. Representing word meaning and order information in a composite holographic lexicon. *Psychological Review* 114.1: 1–37.

Introduces a random vector accumulation model that works on the same principle of Hebbian learning as HAL but where each word is initialized with a random vector updated based on both semantic context and syntactic position. Model performance successfully accounts for a wide variety of semantic and syntactic tasks. Argues for simplicity in processing mechanisms and representational structure. Available online by subscription.

Kwantes, P. J. 2005. Using context to build semantics. *Psychonomic Bulletin & Review* 12.4: 703–710.

Introduces a model of semantic memory rooted in a model of retrieval from episodic memory. Compares word vector construction to LSA. Advocates a model that unifies semantic and episodic memories as emerging from the same mechanisms. Available online by subscription.

Landauer, T. K., and S. T. Dumais. 1997. A solution to Plato's problem: The latent semantic analysis theory of acquisition, induction, and representation of knowledge. *Psychological Review* 104.2: 211–240.

Proposes latent semantic analysis as a means to understand the process by which humans extract semantic information from statistical redundancies in language. LSA operates on a word-by-document count matrix, applies statistical models of dimensionality reduction to produce word similarities. Available online by subscription.

Lund, K., and C. Burgess. 1996. Producing high-dimensional semantic spaces from lexical co-occurrence. *Behavior Research Methods, Instruments, & Computers* 28.2: 203–208.

Introduces the hyperspace analogue to language (HAL) as a means of extracting statistical information from a language corpus. HAL slides a fixed window across a text and counts occurrences within the window. Model performance accurately reproduces human performance in semantic priming. Available online by subscription.

Mikolov, T., I. Sutskever, K. Chen, G. S. Corrado, and J. Dean. 2013. Distributed representations of words and phrases and their compositionality. In *Advances in neural information processing systems*. Edited by C. J. C. Burges, L. Bottou, M. Welling, Z. Ghahramani, and K. Q. Weinberger. 3111–3119. Curran Associates, Inc.

Scales up Elman's model using temporal steps and other methods in order to increase learning potential. Subsequent Word2Vec model performs well on semantic and computational linguistic tasks. Available online by subscription.

Pennington, J., R. Socher, and C. Manning. 2014. Glove: Global vectors for word representation. In *Association for Computational Linguistics*: *Proceedings of the 2014 conference on empirical methods in natural language processing (EMNLP)*. Edited by A. Moschitti, B. Pang, and A. W. Daelemans, 1532–1543. Doha, Qatar.

Evaluates a model based on a word-by-word matrix rather than a word-by-document (LSA) or a sliding window (HAL). Model performance accurately accounts for human behavior on analogy tasks. Argues for clarity in the construction of models that account for linguistic statistical regularities.

Turney, P. D., and P. Pantel. 2010. From frequency to meaning: Vector space models of semantics. *Journal of Artificial Intelligence Research* 37:141–188.

Reviews literature on vector space models and evaluates the varied applications and effectiveness of such models. Available online by subscription.

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