Systematicity and Specialization in Semantics: A Computational Account of Optic Aphasia

Sean McGuire
sean@crab.psy.cmu.edu

David C. Plaut
plaut@cmu.edu

Department of Psychology
Carnegie Mellon University and the
Center for the Neural Basis of Cognition
Pittsburgh PA 15213-3890

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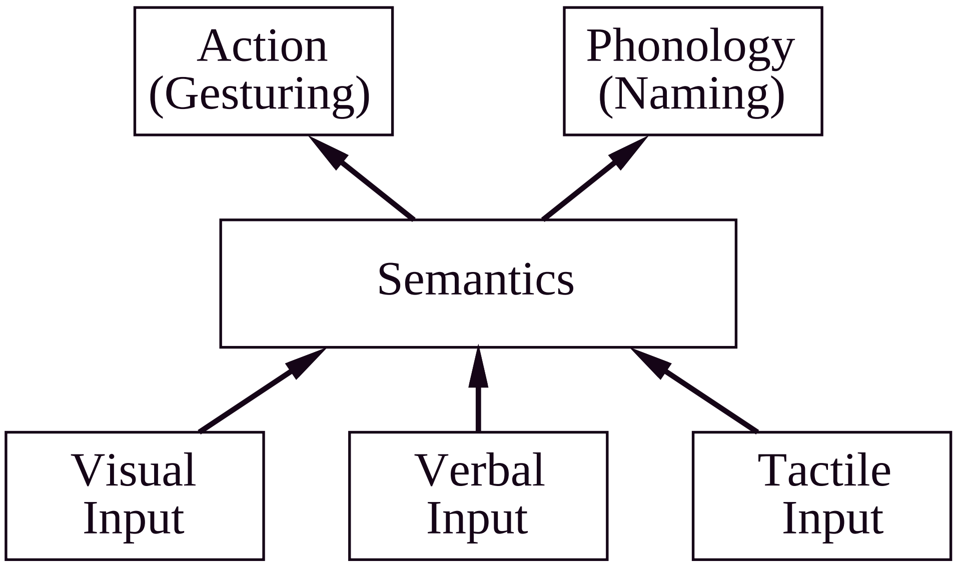
Abstract

Modality-specific naming deficits, such as optic aphasia, have been taken as evidence that semantics is organized into distinct modality-specific subsystems. We adopt an alternative view in which semantics is a learned, internal representation within a parallel distributed processing system that maps between multiple input and output modalities. We show that the robustness of a task to damage depends critically on its systematicity, and that modality-specific naming deficits can arise because naming is an unsystematic task.

Background

What is the organization of semantic knowledge of objects?

- **Standard view:** A single, amodal semantic system
  (Caramazza et al., 1990; Hillis & Caramazza, 1995; Riddoch et al., 1988)

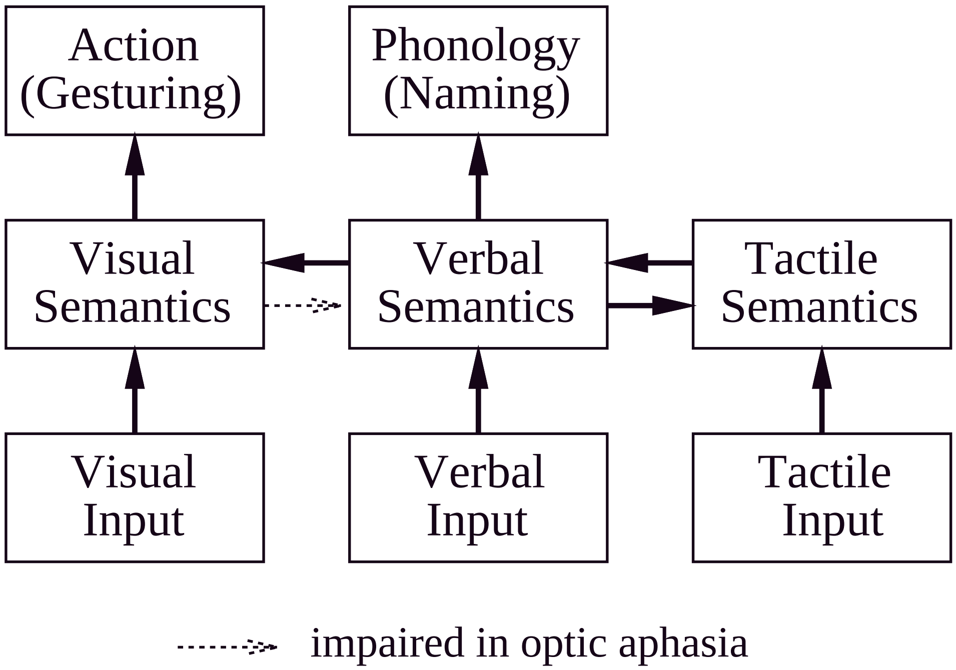


- **Challenge:** Performance of brain-damaged patients with modality-specific naming disorders (e.g., optic aphasia)
  (Gil et al., 1985; Lhermitte & Beauvois, 1973; Riddoch & Humphreys, 1987)
  - Impaired naming from vision
  - Preserved recognition/comprehension from vision
    (e.g., as demonstrated by gesturing the object's use)
  - Preserved naming from other modalities (e.g., touch, audition)
  - Analogous syndromes for tactile input (Beauvois et al., 1978) and for auditory input (Denes & Semenza, 1975)

No location of damage within a box-and-arrow unitary semantics model yields this pattern of performance.

- **Alternative view:** Modality-specific semantic systems

(Beauvois, 1982; Lhermitte & Beauvois, 1973; Shallice, 1987; Warrington, 1975)



Problems: unparsimonious, post-hoc, poor accounts of semantic acquisition and of cross-modal semantic effects.

Current approach

We explain optic aphasia within a unitary semantic system based on connectionist/parallel distributed processing (PDP) principles:

- **Representation:** Within each modality, similar objects are represented by overlapping distributed patterns of activity.
- **Processing:** Responses are generated by the interactions of large numbers of simple, neuron-like processing units.
- **Learning:** Knowledge is encoded as weighted connections between units whose values are adjusted gradually based on task performance.

Central Hypothesis:

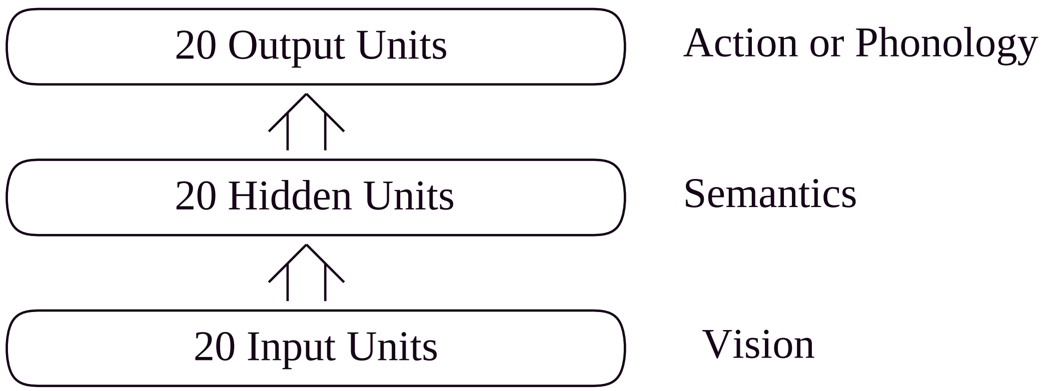
- Semantic representations develop under the pressure of mediating between multiple input and output modalities.
- Tasks differ widely in their degree of *systematicity* (i.e., whether the mapping preserves similarity).
  - Visual naming is unsystematic: Visually similar objects (e.g., BROOM and RAKE) typically have unrelated names.
  - Visual gesturing/action is highly systematic: Visually similar objects often involve similar actions.
- More systematic tasks are more robust to damage.
  - Mild damage from vision to semantics will impair visual naming far more than visual gesturing (and other tests of comprehension) as observed in optic aphasia (see Hillis & Caramazza, 1995; Riddoch & Humphreys, 1987, for similar but unimplemented proposals).

Experiment 1: Demonstration of basic effects

Rate of acquisition and robustness to damage of a network performing a single task that is either systematic (e.g., vision-to-action) or unsystematic (e.g., vision-to-phonology).

Network architecture

- Fully-connected three-layer feedforward network



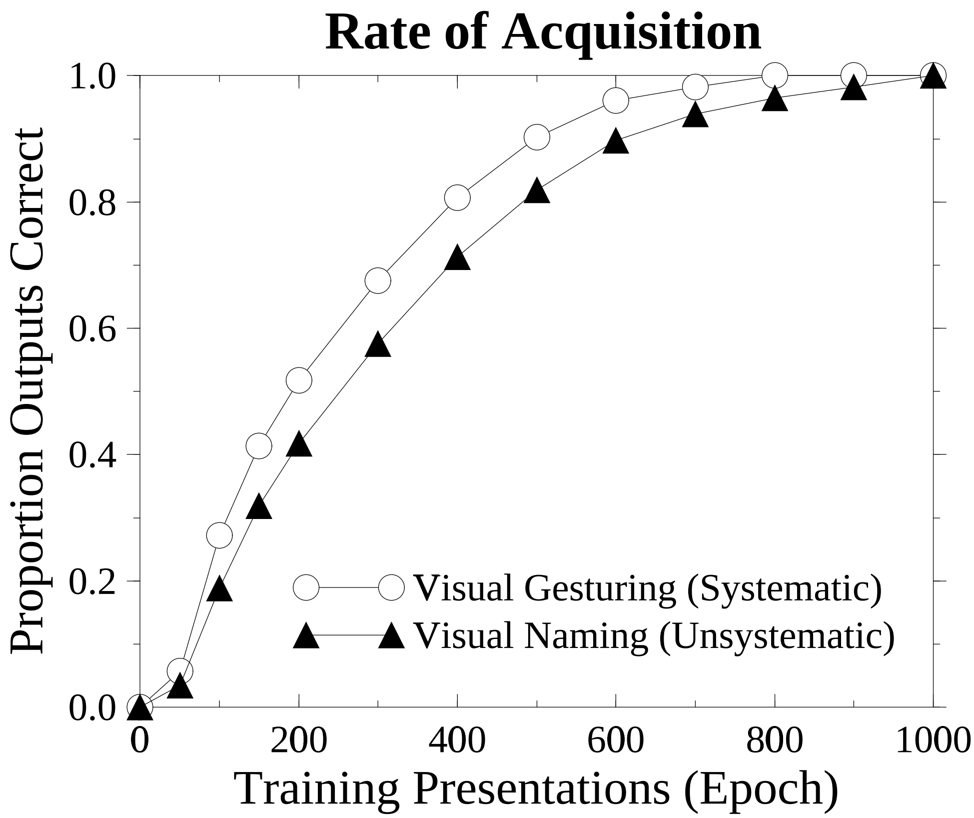
Task definitions

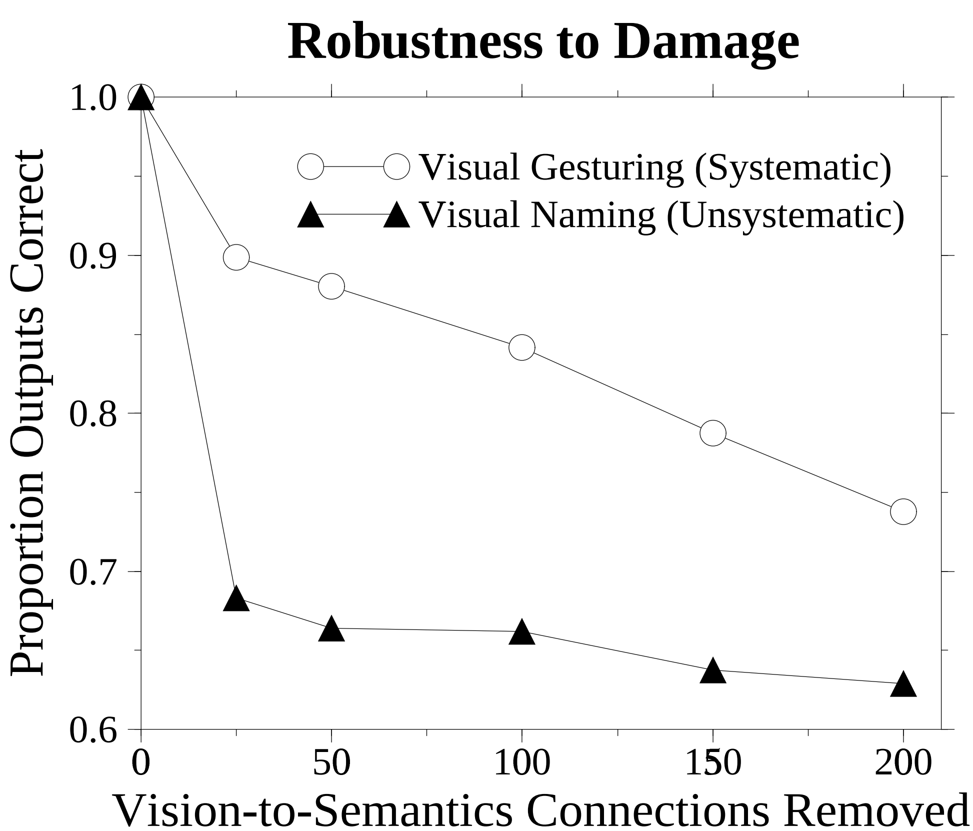
- No attempt to model actual structure of domains
- Abstract tasks with extremes of systematicity:
  - Visual input: 20 random vectors (each bit on with prob. $p = 0.5$)
  - Action output: same 20 vectors (identity mapping)
  - Phonology output: 20 new random vectors (arbitrary mapping)
- Tested 20 random versions of each task

Training and testing procedure

- Back-propagation until sum-squared error < 1.0
- Lesions involve randomly removing some number of Input $\Rightarrow$ Hidden (Vision $\Rightarrow$ Semantics) connections (10 replications for each lesion severity)

Experiment 1: Results





Experiment 1: Conclusions

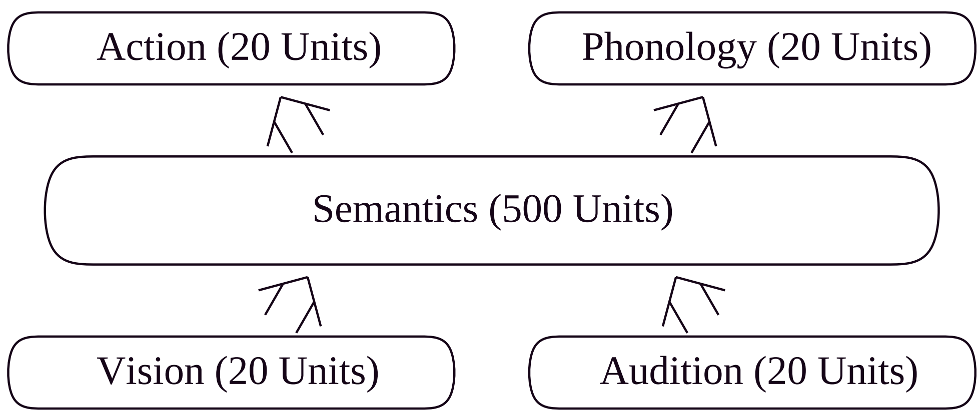
- Task systematicity has a strong influence on rate of acquisition and on robustness to damage in networks.
- The use of an identity mapping to model the relationship of vision and action is an unreasonably strong assumption as this relationship is only partially systematic.

Experiment 2: Simulation of optic aphasia

Network performed four mappings ([vision, audition] X [action, phonology]) through a common hidden (semantic) representation, in which only vision-to-action is systematic.

Network architecture

- Fully-connected feedforward network

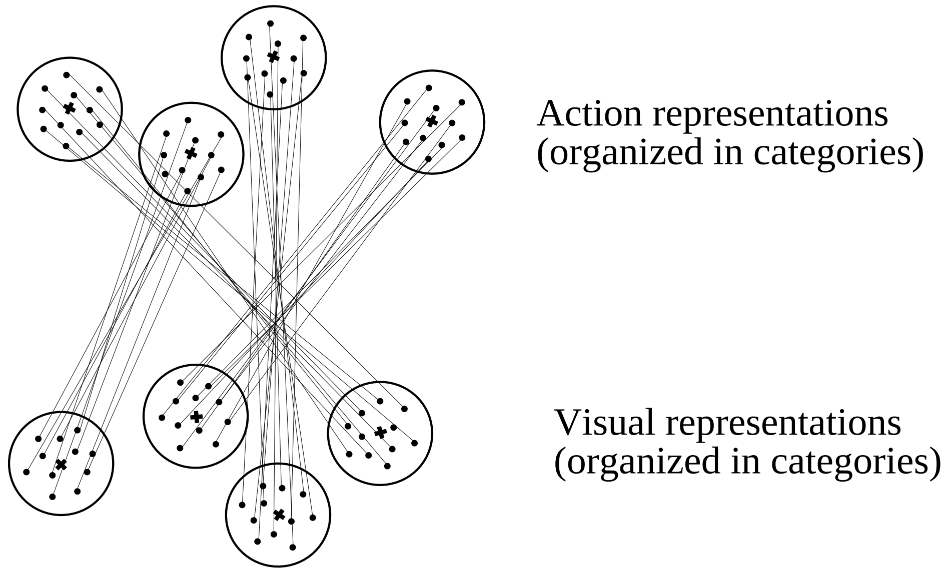


- Large number of hidden units (500) helps with learning multiple arbitrary mappings

Task definitions

- Vision-Action systematicity based on category structure:
  – Visual input: 10 exemplars in each of 10 categories formed by changing 2 randomly chosen features of category prototype (random pattern with $p = 0.5$)
  – Action output: Same procedure as for Visual input; Visual inputs paired with Action outputs such that objects in the same visual category are in the same action category
  – Auditory input: 100 random vectors ($p = 0.5$)
  – Phonology output: 100 new random vectors ($p = 0.5$)

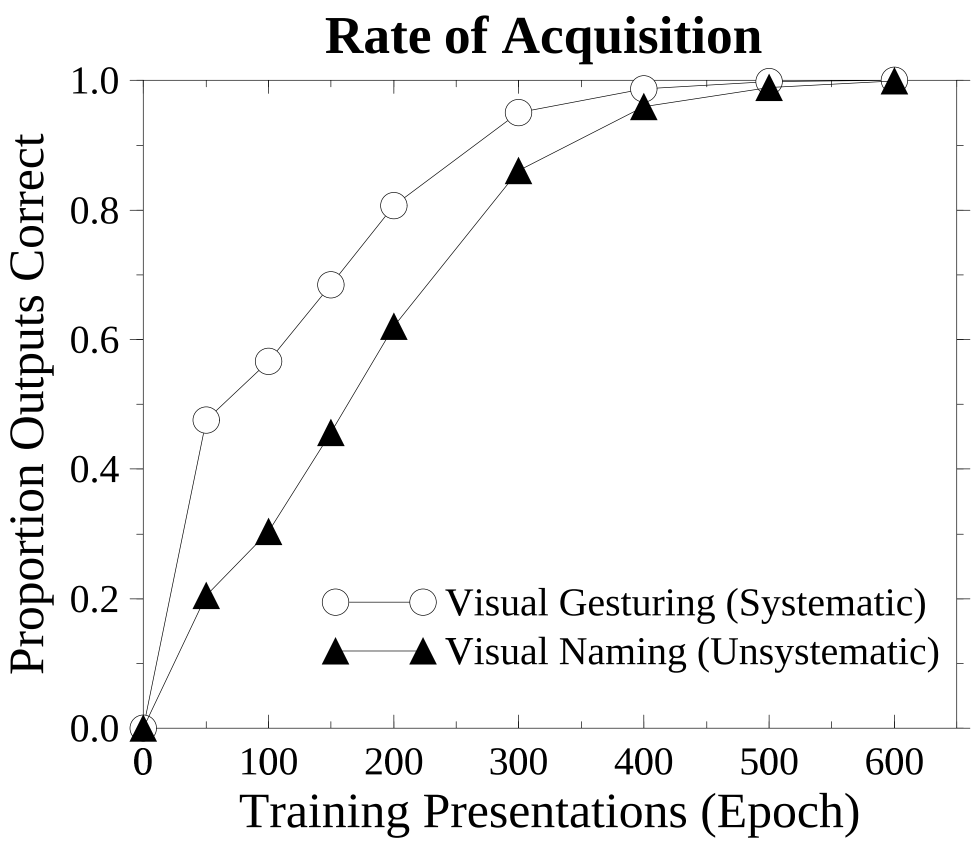
Illustration of Category-Based Systematicity between
Visual (Input) and Action (Output) Representations

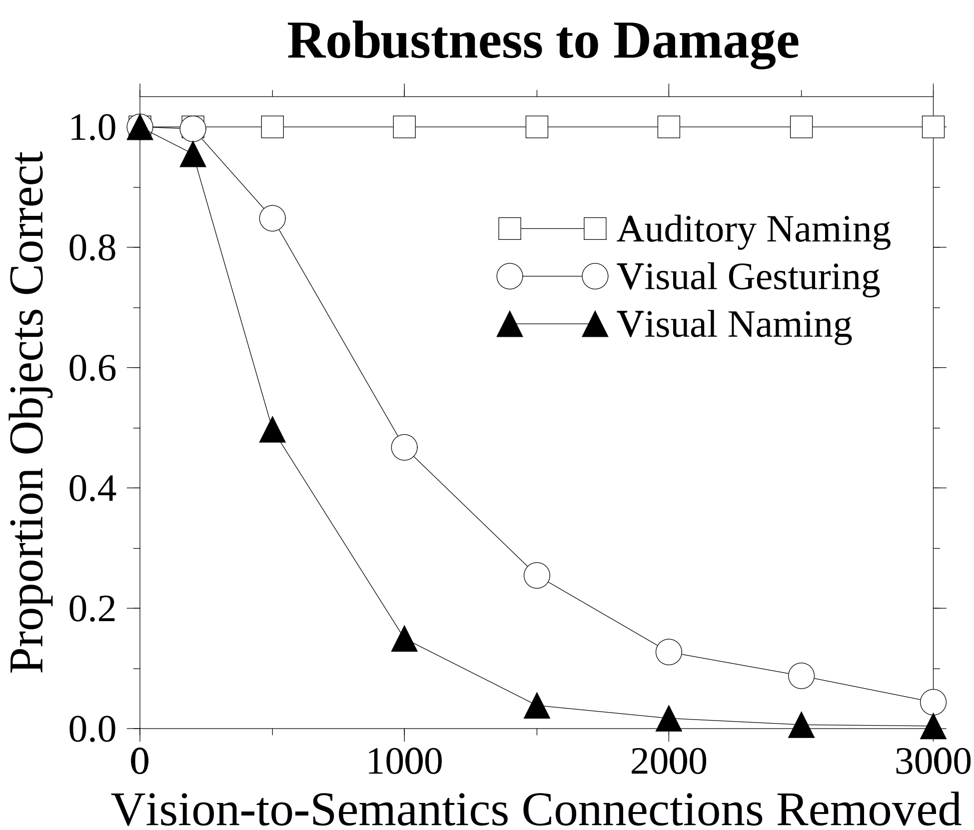


Training and testing procedure

- Back-propagation until all output units within 0.1 of targets on all tasks (621 training presentations of each object in each input modality)
- Lesions involve randomly removing some number of Vision ⇒ Semantics connections (10 replications for each lesion severity)

Experiment 2: Results





Experiment 2: Conclusions

- Damage to Vision ⇒ Semantics connections impairs visual naming (vision-to-phonology) far more than visual gesturing (vision-to-action) and also preserves naming from other modalities (e.g., audition), as found in optic aphasia.

- The quantitative relative impairment on visual naming vs. gesturing (50% vs. 85% correct) is similar to some patients

  45.5% vs. 75.0% for JB (Riddoch & Humphreys, 1987)

  but not as extreme as others

  69% vs. 100% for JF (Lhermitte & Beauvois, 1973)
  0% vs. 50% for Coslett and Saffran's (1989) patient

- Relative task systematicity is an important factor in understanding optic aphasia but may not provide a complete explanation.
  - Also no clear extension to analogous syndrome for auditory input, given the lack of systematicity between audition and action.

- Full account may require *some degree* of modality-based specialization within semantics.

Experiment 3: Topologically-biased learning

Introduce bias into learning favoring "short" connections and "nearby" hidden units (cf. Jacobs & Jordan, 1992)

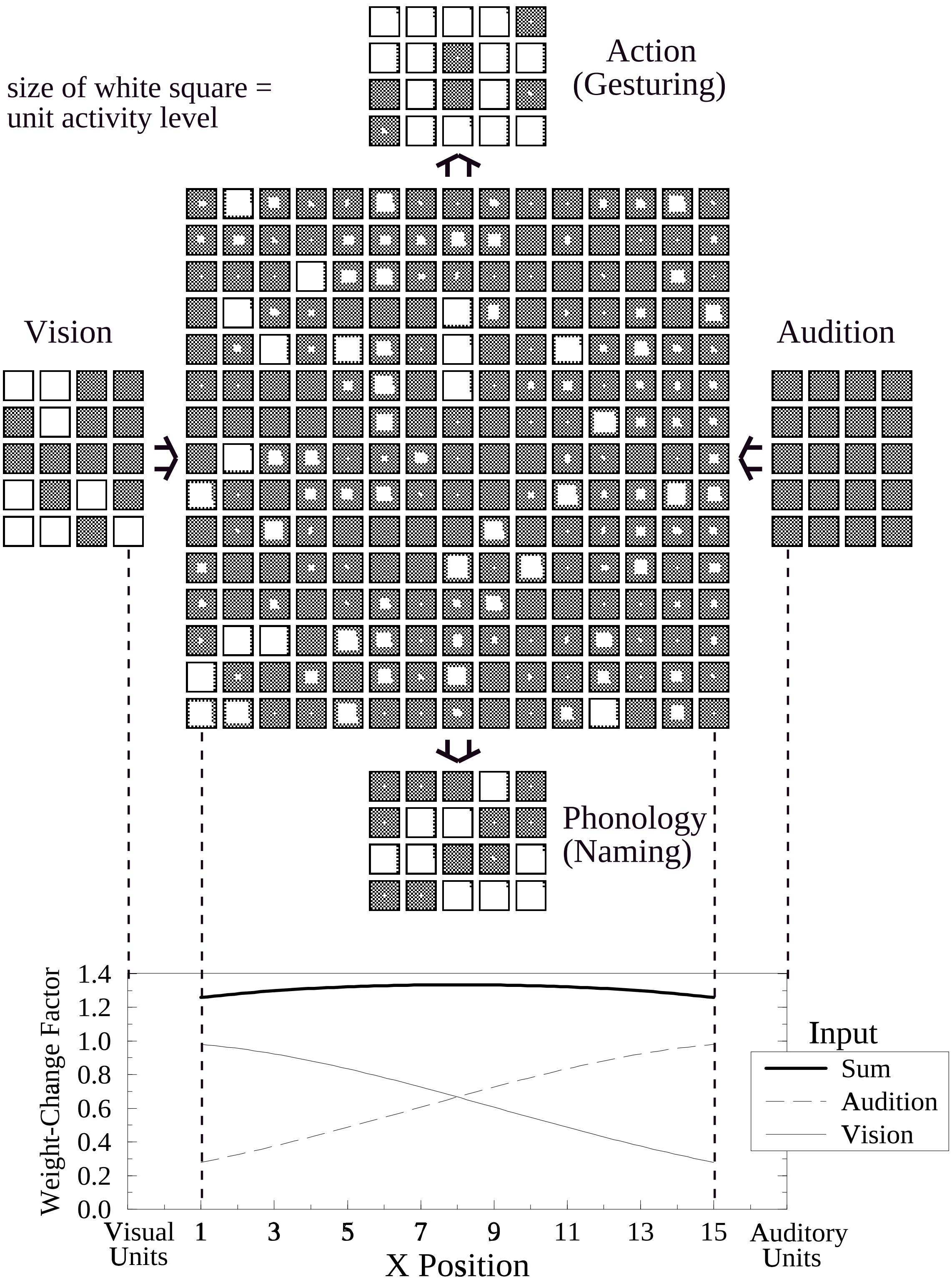
- Units are assigned (2D) positions with hidden units located between input and output units; connections thus have (Euclidean) length.
- Effectiveness of learning (magnitude of weight changes) scaled by a monotonically decreasing (Gaussian) function of connection length.
- Learning is initially strongest for connections to hidden units that are near inputs and outputs, and only engages more distant hidden units as necessary.

Motivation

- High-level representations for input and output modalities have distinct neuroanatomic localizations.
- Strong neurobiological bias favoring short axons (in part because total axon volume must fit within skull).
- Distance-dependent bias on learning should give rise to graded degree of neuroanatomic specialization for combinations of input and output modalities.

Network architecture

- Fully-connected feedforward network
- 225 hidden units in 15x15 grid; input modalities (sides) and output modalities (top and bottom) in 5x4 grids equidistant from hidden layer.
- Learning rate scaled by Gaussian (*SD* = 10) of connection length.
- Hidden (Semantic) units constrained to have strong negative biases.



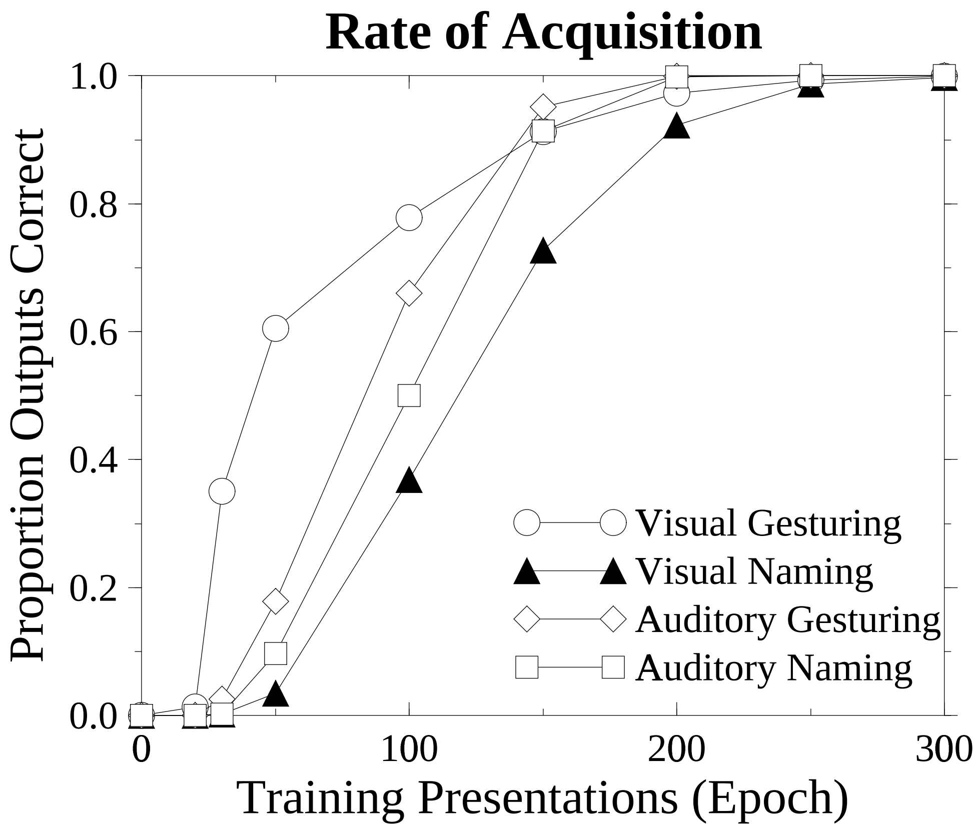
Task definitions

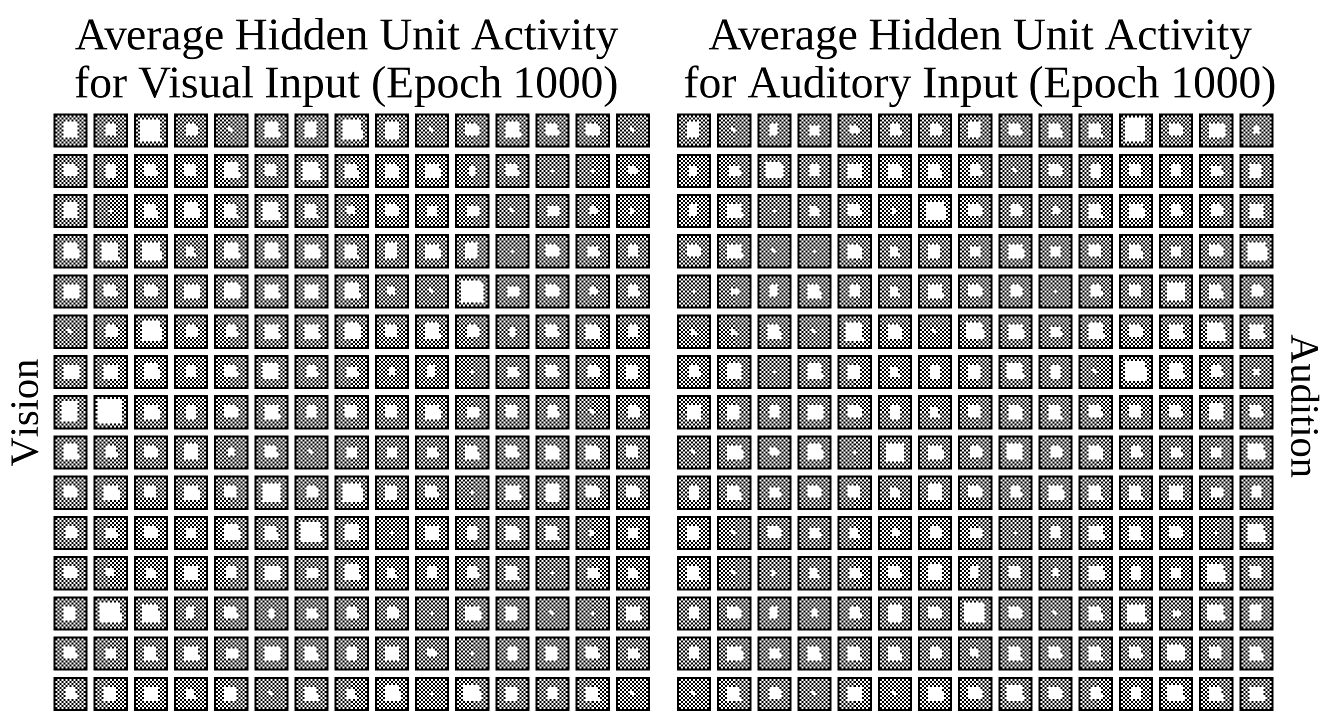
- Same as in Experiment 2

Training procedure

- Back-propagation for 1000 training presentations of each object in each input modality.

Experiment 3: Results



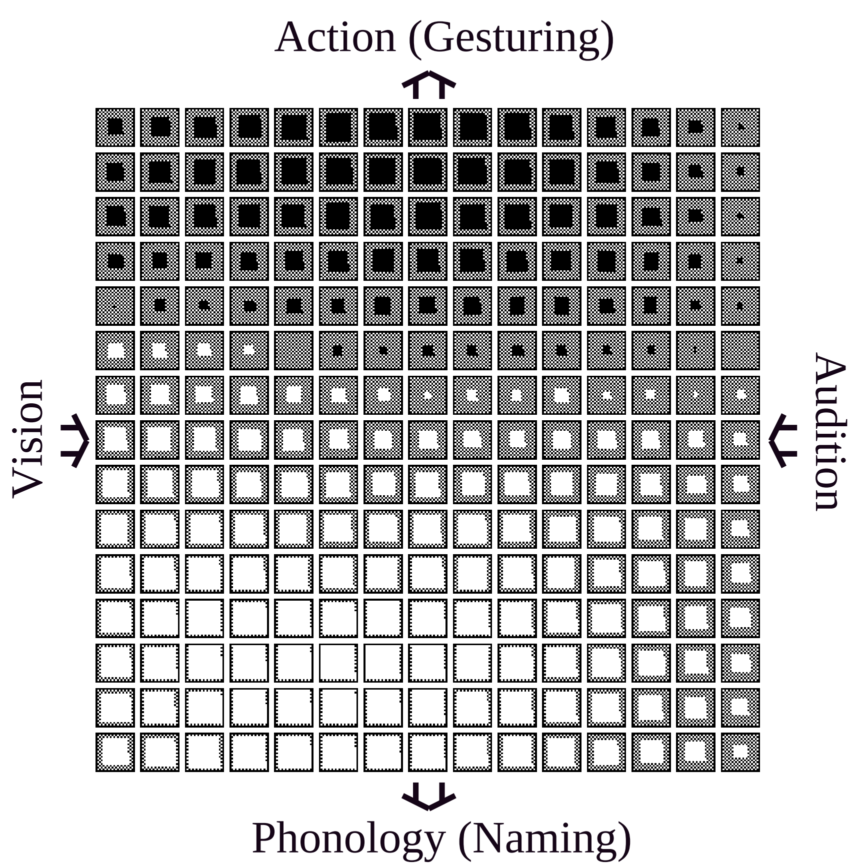


- Distance bias in learning has only a small effect on the distributions of semantic representations of visual vs. auditory input.

Effects of Lesion Position

- For lesions, probability of removing each Vision ⇒ Semantics connection is a Gaussian function of the distance of the Semantic unit from some specified lesion location; *SD* of Gaussian controls the severity of lesion.

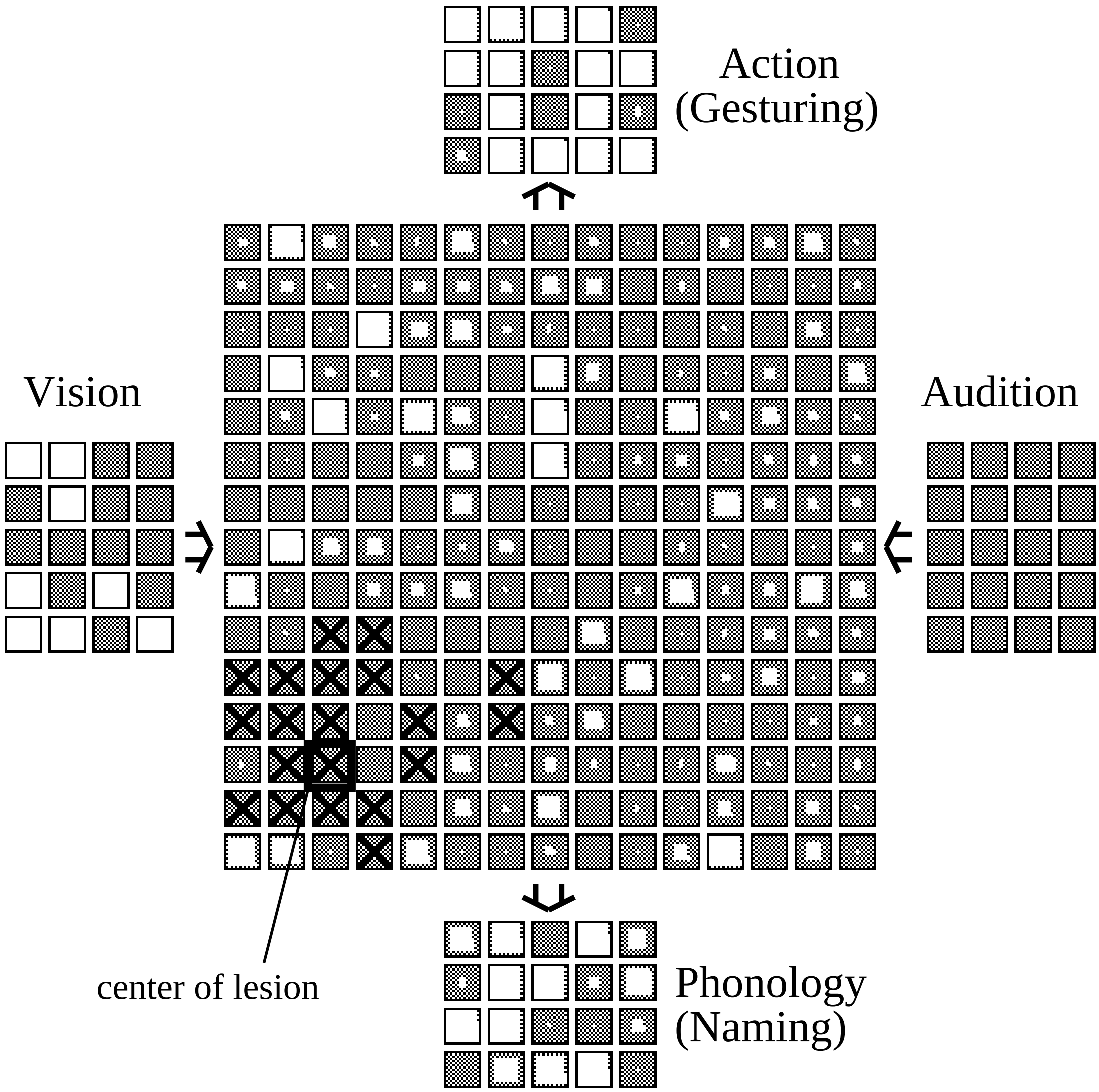
- Plotted below for each Semantic location is visual gesturing performance minus visual naming performance after Vision ⇒ Semantics lesions centered at that location (*SD* = 2; 10 reps each).
  - White = naming $<$ gesturing; Black = naming $>$ gesturing
  - Size of square reflects absolute numeric difference in performance (e.g., full white square = 0% at naming, 100% at gesturing).

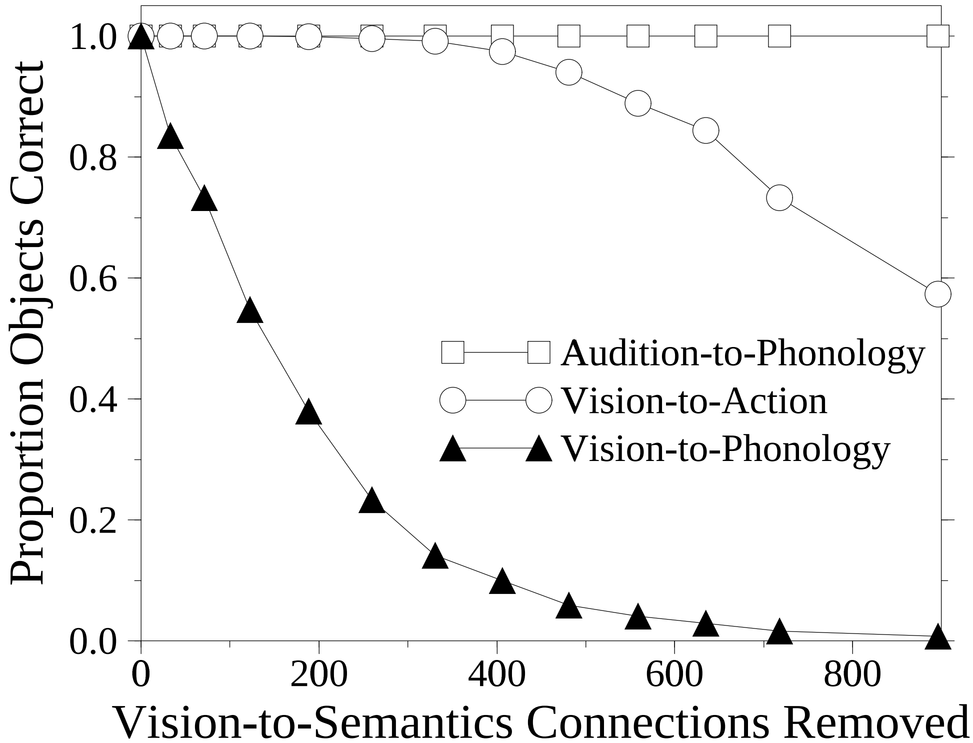


- Greater extent and magnitude of relative impairment on visual naming (white squares) due to lack of systematicity of naming vs. gesturing.

Effects of Lesion Severity

- Lesions to Vision ⇒ Semantics connections at a single semantic location across a range of severities (40 replications each).
- Note that hidden unit lesion is shown to illustrate location and extent of damage (*SD* = 2.0); actual lesions are to incoming connections.




Proportion Objects Correct
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
Vision-to-Semantics Connections Removed
Audition-to-Phonology
Vision-to-Action
Vision-to-Phonology

Experiment 3: Conclusions

- Introducing a bias on learning favoring short connections gives rise to a graded degree of topological specialization in hidden representations.
  - The network does **not** consist of separate modality-specific semantic systems—both visual and auditory input engage the entire semantic system.
- Particular tasks—combinations of input and output modalities—come to rely more strongly on hidden units that are located near the two modalities.
- Damage to these partially specialized regions (or their incoming connections) gives rise to greater relative impairments on the corresponding tasks, particularly if they are unsystematic (e.g., visual naming).

Summary

- Semantic knowledge for objects is typically thought to be represented within a single, amodal semantic system, but this view is challenged by brain-damaged patients with modality-specific naming disorders (e.g., optic aphasia).
  - Optic aphasic patients are selectively impaired at naming objects when presented visually (but not in other modalities) even though they can demonstrate recognition/comprehension of the objects (e.g., by gesturing their use appropriately).
- An important factor in understanding the relative robustness of tasks to damage is their degree of *systematicity*: the extent to which similar inputs map to similar outputs.
- Connectionist simulations show that selective impairments in visual naming can arise from damage to visual inputs to a single, amodal semantic system because visual naming is an unsystematic task whereas visual gesturing (and other tests of comprehension) are far more systematic.
- The relative impairment of visual naming vs. gesturing is further exacerbated if the network also develops a graded degree of specialization within semantics due to a topological bias favoring short connections.
- The results suggest that a single, amodal semantic system with some degree of topological specialization, when implemented as a connectionist network, can provide a full account of optic aphasia (and other modality-specific naming disorders).

References

Beauvois, M.-F. (1982). Optic aphasia: A process of interaction between vision and language. *Proceedings of the Royal Society of London, Series B, 298*, 35–47.

Beauvois, M.-F., Saillant, B., Meininger, V., & Lhermitte, F. (1978). Bilateral tactile aphasia: A tacto-verbal dysfunction. *Brain*, *101*, 381–401.

Caramazza, A., Hillis, A. E., Rapp, B. C., & Romani, C. (1990). The multiple semantics hypothesis: Multiple confusions? *Cognitive Neuropsychology*, *7*, 161–189.

Coslett, H. B., & Saffran, E. M. (1989). Preserved object recognition and reading comprehension in optic aphasia. *Brain, 112*, 1091–1110.

Denes, G., & Semenza, C. (1975). Auditory modality-specific anomia: Evidence from a case of pure word deafness. *Cortex, 11*, 401–411.

Gil, R., Pluchon, C., Toullat, G., Michenau, D., Rogez, R., & Levevre, J. P. (1985). Disconnexion visuo-verbale (aphasie optique) pour les objets, les images, les couleurs et les visages avec alexie "abstractive". *Neuropsychologia*, *23*, 333–349.

Hillis, A. E., & Caramazza, A. (1995). Cognitive and neural mechanisms underlying visual and semantic processing: Implications from "optic aphasia". *Journal of Cognitive Neuroscience*, *7*, 457–478.

Jacobs, R. A., & Jordan, M. I. (1992). Computational consequences of a bias toward short connections. *Journal of Cognitive Neuroscience*, *4*, 323–336.

Lhermitte, F., & Beauvois, M.-F. (1973). A visual-speech disconnexion syndrome: Report of a case with optic aphasia, agnosic alexia and colour agnosia. *Brain*, *96*, 695–714.

Riddoch, M. J., & Humphreys, G. W. (1987). Visual object processing in optic aphasia: A case of semantic access agnosia. *Cognitive Neuropsychology*, *4*, 131–185.

Riddoch, M. J., Humphreys, G. W., Coltheart, M., & Funnell, E. (1988). Semantic systems or system? Neuropsychological evidence re-examined. *Cognitive Neuropsychology*, *5*, 3–25.

Shallice, T. (1987). Impairments of semantic processing: Multiple dissociations. In M. Coltheart, G. Sartori, & R. Job (Eds.), *The cognitive neuropsychology of language* (pp. 111–128). Hillsdale, NJ: Erlbaum.

Warrington, E. K. (1975). The selective impairment of semantic memory. *Quarterly Journal of Experimental Psychology*, *27*, 635–657.

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