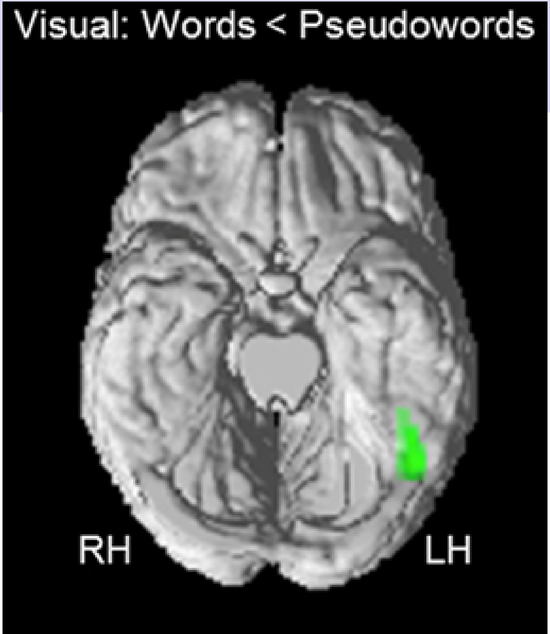
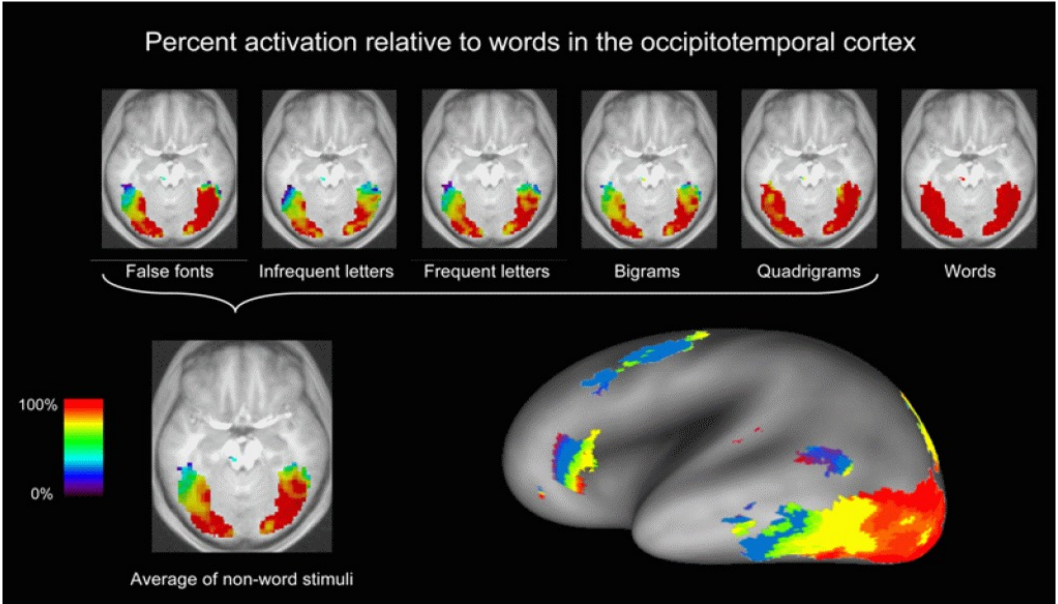
Visual word-form area (VWFA)

(Kanwisher et al., 1997; Ludersdorfer et al., 2013)

- Cortical region in left ventral occipito-temporal cortex that responds more strongly to words (MAKE) than to pseudowords (MAVE), and more strongly to either than to non-orthographic stimuli (e.g., objects, faces)

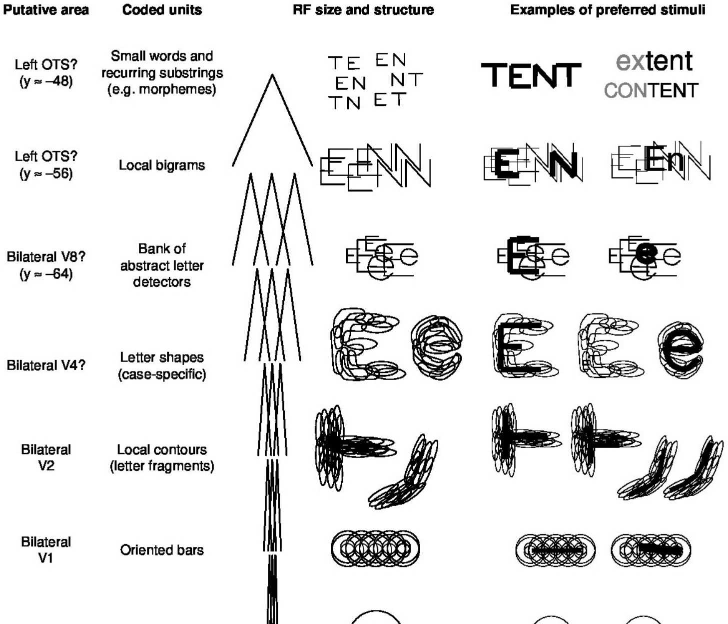


Hierarchical response to orthographic structure (Vinckier et al., 2007)



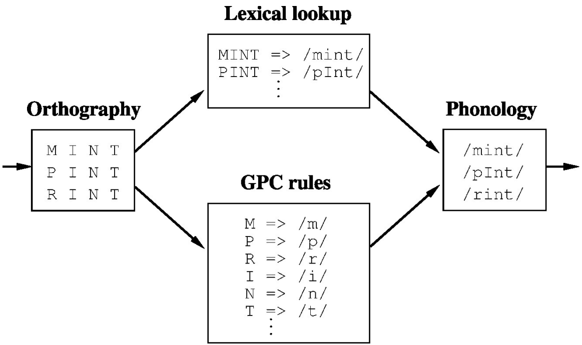
Hierarchical orthographic representations

(Dehaene et al., 2005)



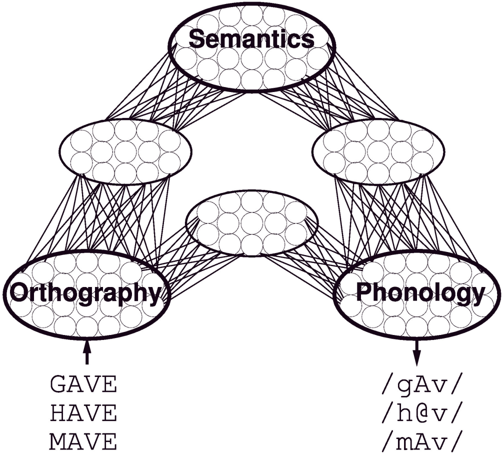
Dual-route theory of word reading

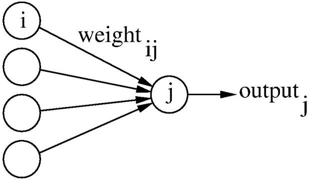
- Systematic spelling-sound knowledge takes the form of grapheme-phoneme correspondence (GPC) rules (e.g., $\mathrm{G} \Rightarrow$ /g/, $\mathrm{A\_E} \Rightarrow$ /A/)
- Applying GPC rules produces correct pronunciations for *regular* words (GAVE) and *nonwords* (MAVE), but incorrect pronunciations for *exception* words (HAVE)
- Exception words therefore require a separate lexical look-up procedure



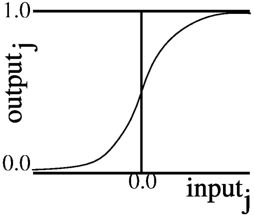
A neural-network framework for word reading

Triangle model (Seidenberg & McClelland, 1989; Plaut et al., 1996; Harm & Seidenberg, 2004)





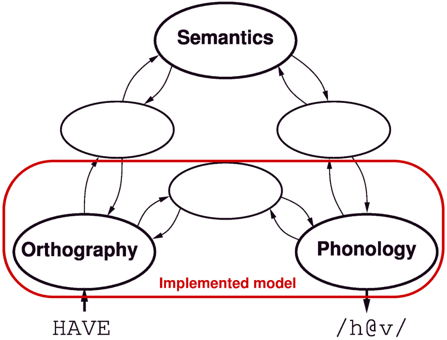
$$\text{input}_j = \sum_i \text{output}_i \times \text{weight}_{ij}$$



Seidenberg and McClelland (1989)

Method

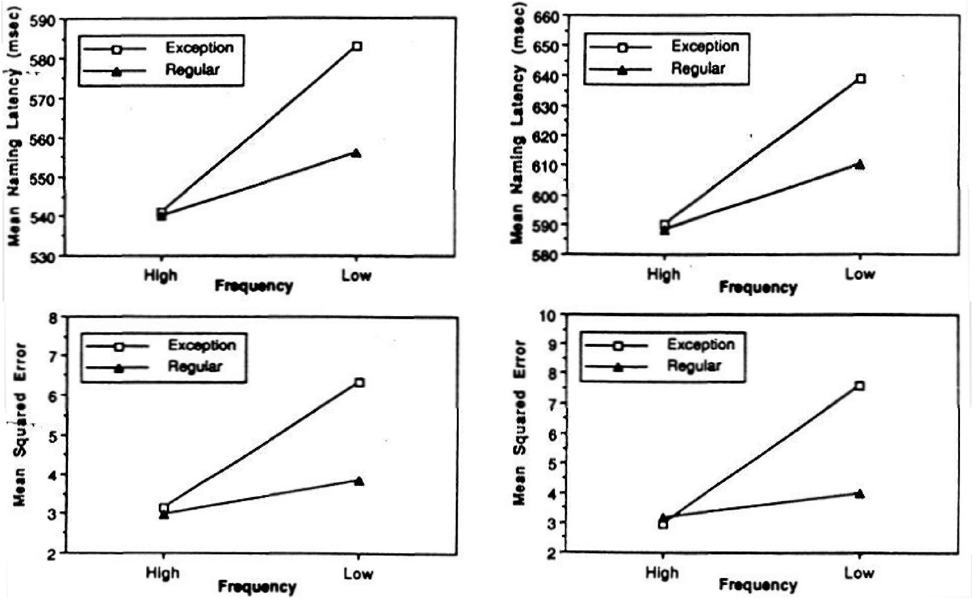
- Feedforward network trained with back-propagation to pronounce 2897 monosyllabic words, sampled according to log frequency
- Representations of orthography and phonology based on context-sensitive triples of letters or phonemic features
  (same as Rumelhart & McClelland past-tense model)



Results

- After 250 training epochs, network correctly pronounces 97.3% of words, including most exception words
- Error pattern accounts for many empirical effects of frequency and spelling-sound regularity on naming latencies
- **Failed to read pronounceable nonwords as accurately as skilled readers**

Frequency and regularity effects on naming latencies (and model error)



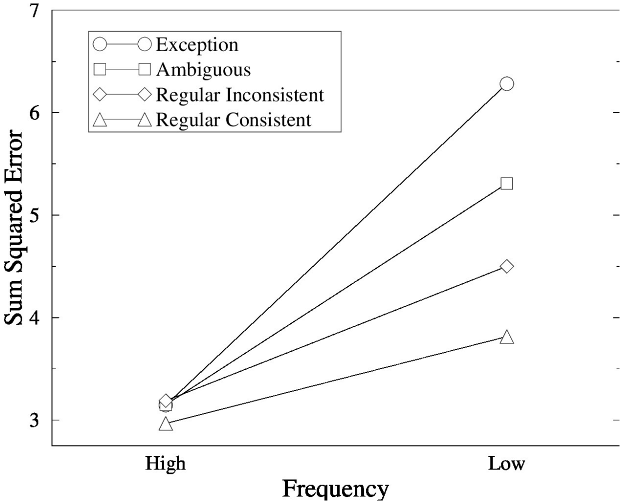
Frequency-by-consistency interaction (SM89)

Regular Consistent
Many *friends* and no *enemies*
LATE, DUST

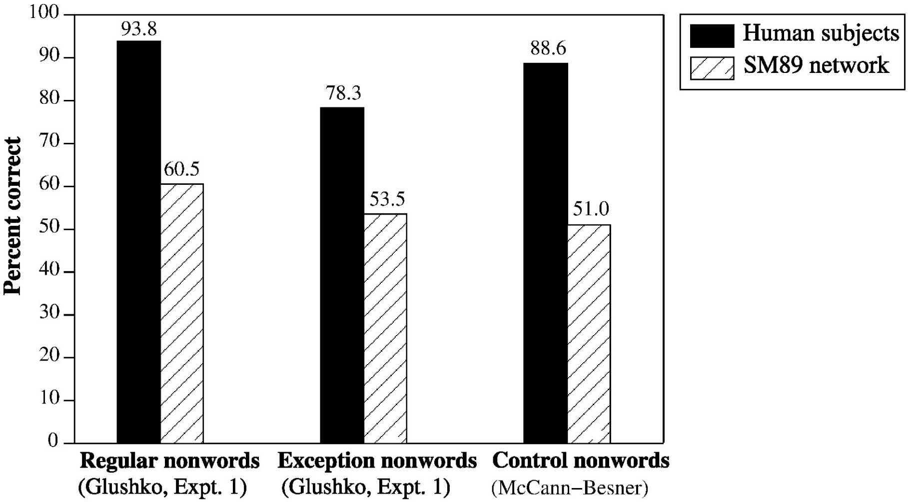
Regular Inconsistent
Many friends but at least one enemy
GAVE (cf. HAVE), MINT (cf. PINT)

Ambiguous
About equal friends and enemies
DOWN, KNOWN; POUR, SOUR

Exception
Few if any friends and many enemies
HAVE (cf. GAVE), PINT (cf. MINT)



Nonword reading (Seidenberg & McClelland, 1989)



HEAN
(DEAN)

HEAF
(DEAF)

FRANE
(BRANE)

The "dispersion" problem

- LOG, GLAD, and SPLIT have no triples in common (no similarity despite sharing "L")

LOG			${}_{*}L_{O}$	${}_{L}O_{G}$	${}_{O}G_{*}$
GLAD		${}_{*}G_{L}$	${}_{G}L_{A}$	${}_{L}A_{D}$	${}_{A}D_{*}$
SPLIT	${}_{*}S_{P}$	${}_{S}P_{L}$	${}_{P}L_{I}$	${}_{L}I_{T}$	${}_{I}T_{*}$

Capturing orthographic and phonological structure

- *Phonotactic constraints*: Possible phoneme sequences are strongly constrained by the structure of the articulatory system and by language-specific learning.
- *Alphabetic principle*: Parts of written words (graphemes) correspond to parts of pronunciations (phonemes).

Can rely on phonotactic constraints to order phonemes within consonant/vowel clusters

	Onset				Vowel			Coda		
	S	P	G	L	O	A	I	G	D	T
LOG				L	O			G		
GLAD			G	L		A			D	
SPLIT	S	P		L			I			T

Representations

Phonology

Onset

s S C   z Z j f v T D p b t d k g m n h   l r w y

Vowel

a @ e i o u A E I O U W Y ^

Coda

r   l   m n N   b g d   ps ks ts   s z   f v p k   t   S Z T D C j

Orthography

Onset

Y S P T K Q C B D G F V J Z L M N R W H CH GH GN PH PS RH SH TH TS WH

Vowel

E I O U A Y AI AU AW AY EA EE EI EU EW EY IE OA OE OI OO OU OW OY UE UI UY

Coda

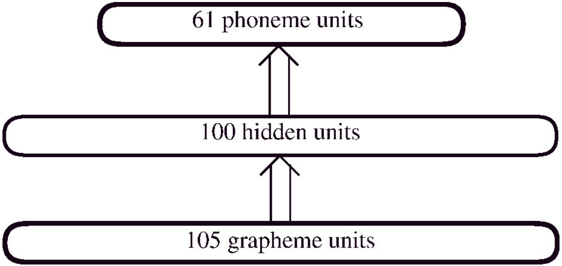
H R L M N B D G C X F V J S Z P T K Q BB CH CK DD DG

FF GG GH GN KS LL NG NN PH PP PS RR SH SL SS TCH TH TS TT ZZ U E ES ED

Simulation: Feedforward network (Plaut et al., 1996)

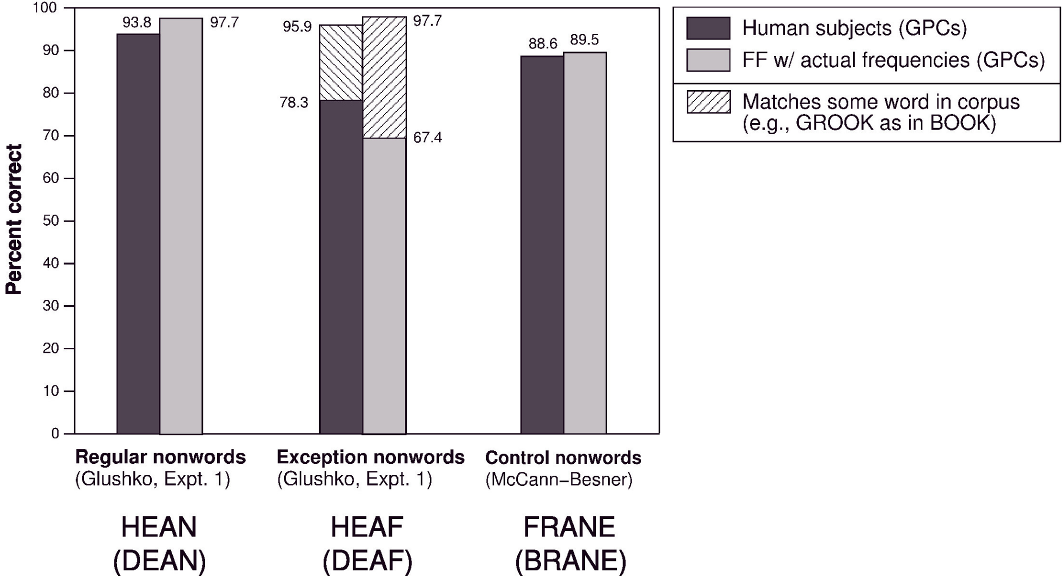
Training

- Used grapheme- and phoneme-based representations that condense spelling-sound regularities
- Trained with on 2998 monosyllabic words (SM89 corpus plus additional 101 words) using **actual word frequencies** to scale weight changes

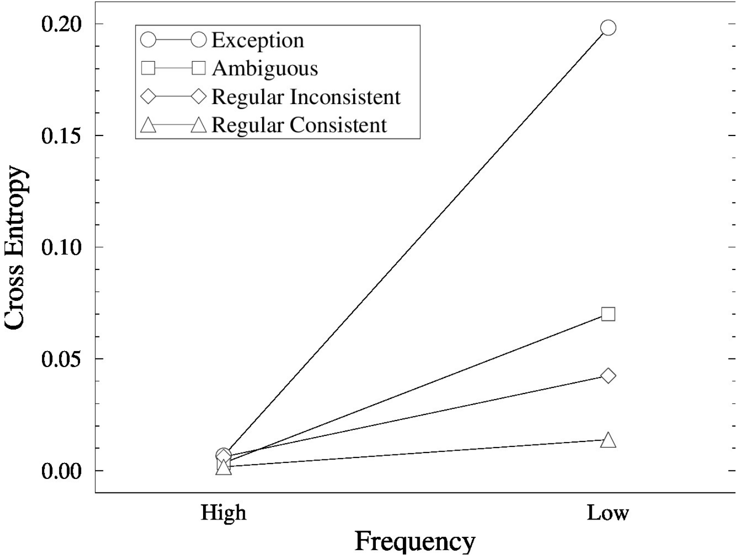


- Error measured by **cross-entropy**: $C = -\sum_j t_j \log(a_j) + (1 - t_j)\log(1 - a_j)$
- Adaptation of connection-specific learning rates (delta-bar-delta; Jacobs, 1988)
- After 300 epochs, network is pronounces *entire* training corpus correctly (100% correct)

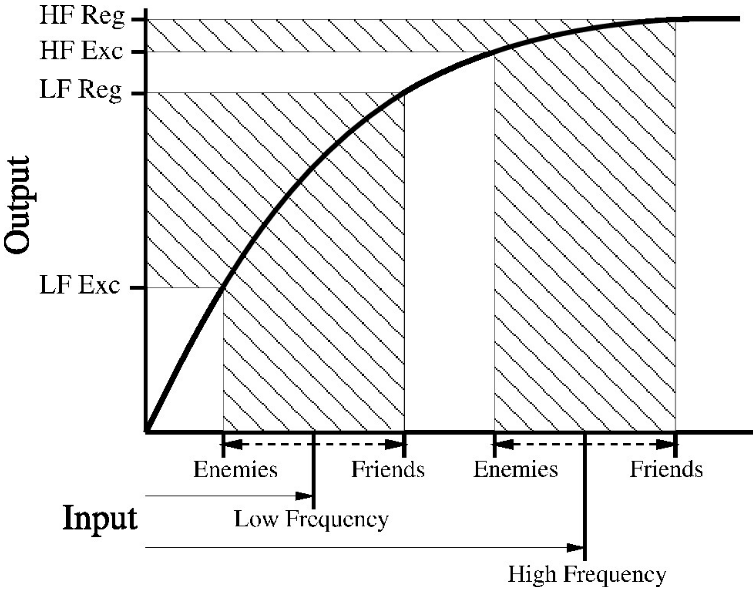
Nonword reading (Plaut et al., 1996)



Frequency-by-consistency interaction



Frequency-by-consistency interaction

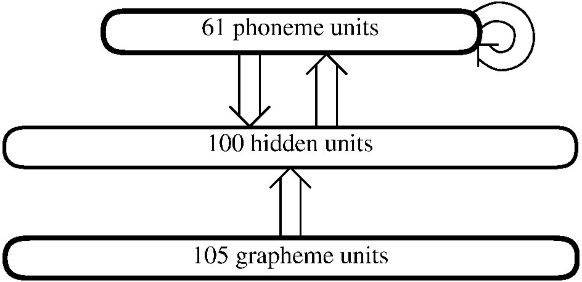


Friends: similiar trained patterns with **same** target

Enemies: similiar trained patterns with **different** target

Increases of either frequency or regularity/consistency provides **diminishing returns** due to asymptotic nature of sigmoid function

Simulation: Attractor network

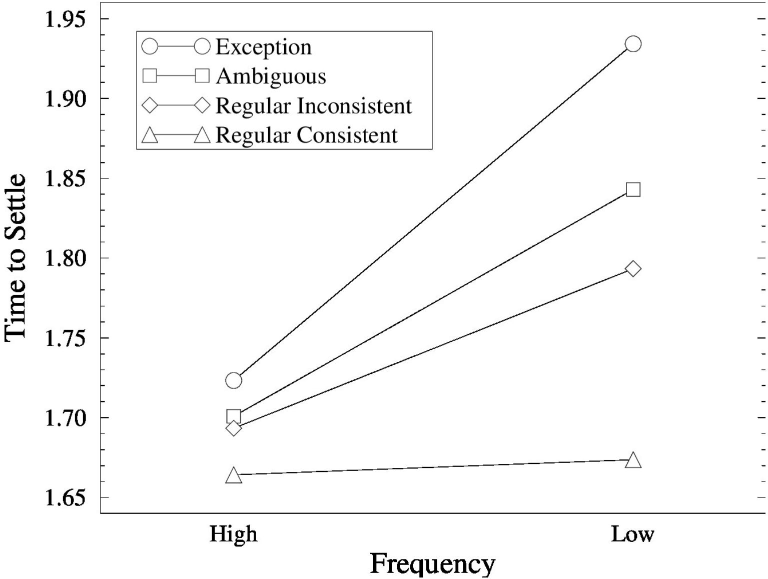


$$n_j^{[t]} = \tau \sum_i a_i^{[t-\tau]} w_{ij} + (1-\tau)\, n_j^{[t-\tau]}$$

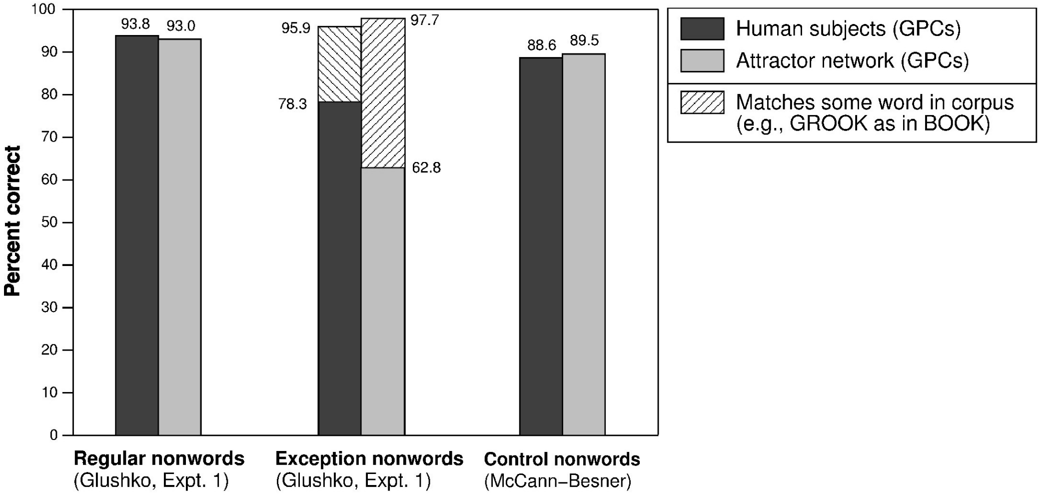
$$a_j^{[t]} = \frac{1}{1 + \exp\left(-\eta_j^{[t]}\right)}$$

- Trained with a continuous version of back-propagation through time (Pearlmutter, 1989) using actual word frequencies, cross-entropy, and delta-bar-delta
- Run for 2.0 units of time, receiving no error before time 1.0; discretization $\tau = 0.2$ reduced to 0.01 at end of training
- During testing, network responds when phoneme states stop changing
- After 1900 epochs, the network pronounces all but 25 words correctly (99.2% correct)

Frequency-by-consistency interaction (attractor network)

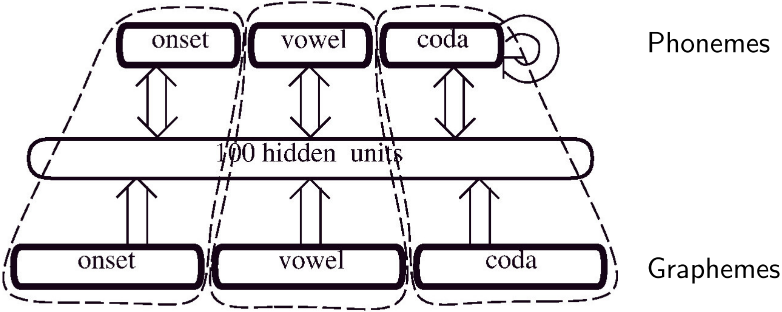


Nonword reading (attractor network)



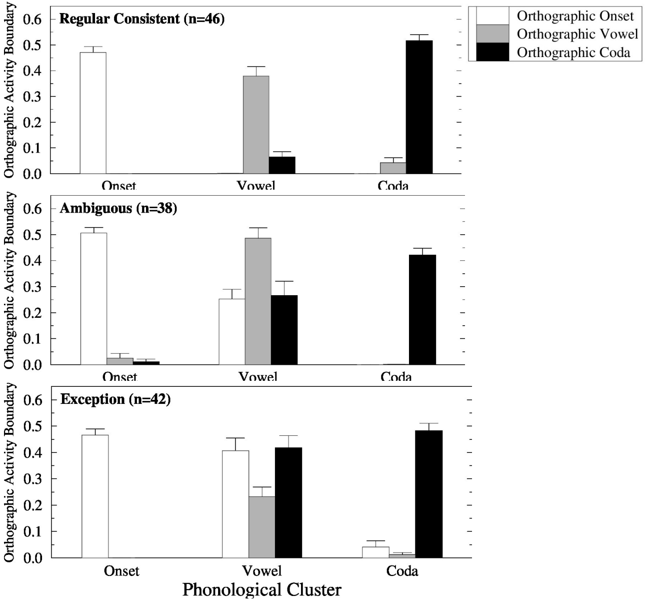
HEAN (DEAN) HEAF (DEAF) FRANE (BRANE)

Generalization with componential attractors



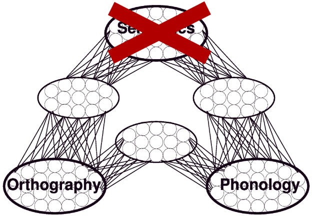
- Very strong orthography-phonology systematicity *within* consonant clusters (less for vowels); relative independence *between* clusters (except for vowels in exception words)
- Connectionist learning is sensitive to which parts of the input reliably predict (e.g., are correlated with) each part of the output
- Network develops *componential* attractors for words that can recombine to support nonword reading

How do outputs (phonemes) depend on inputs (graphemes)?



- Regulars words are fully componential (each output cluster depend only on corresponding input cluster)
- Vowels in ambiguous and exception words depend on context (surrounding consonant clusters)
- Exception vowels are de-emphasized (misleading)

Acquired "surface" dyslexia



- Brain damage to left temporal lobe (stroke, head injury, or degenerative disease) in premorbidly literate adult
- Severe impairment to **semantics**, or to semantics-phonology mapping
- Nonword reading is generally intact
- Word reading *accuracy* influenced by frequency and regularity/consistency

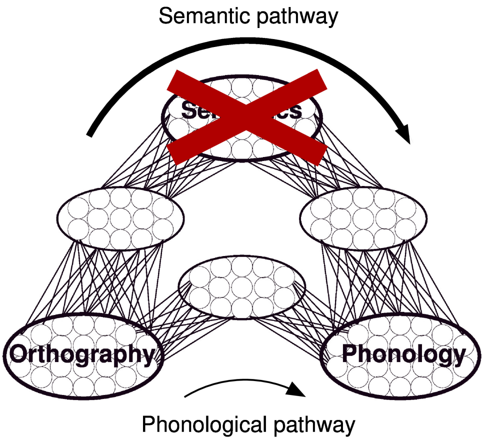
	Correct Performance (%)					
Patient	HF Reg	LF Reg	HF Exc	LF Exc	%Reg's	NW
MP	95	98	93	**73**	90	95.5
KT	100	89	47	**26**	85	100

- Exception words produce *regularization errors*

DEAF	⇒	"deef"	FLOOD	⇒	"flude"	SAID	⇒	"sayed"
GONE	⇒	"goan"	BROAD	⇒	"brode"	STEAK	⇒	"steek"
SHOE	⇒	"show"	SEW	⇒	"sue"	ONE	⇒	"own"

Division of labor between pathways

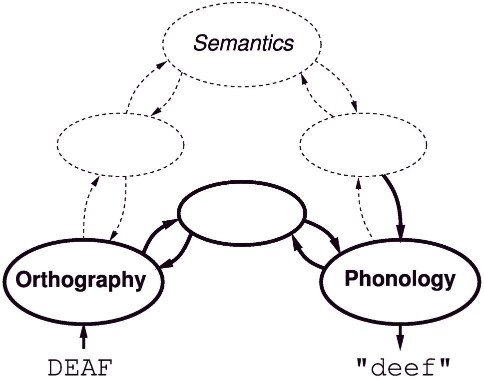
- Phonological and semantic pathways combine to support oral reading
- As semantic pathway develops, demands on phonological pathway diminish
- Impairment of semantic pathway by brain damage reveals latent limitations of **intact** phonological pathway

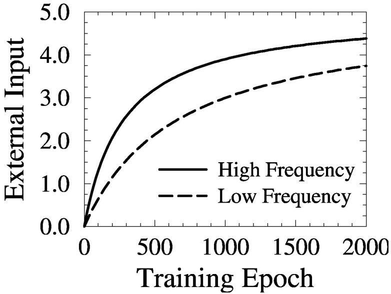


$\Rightarrow$ **Reading (low-frequency) exception words should rely on semantic support**

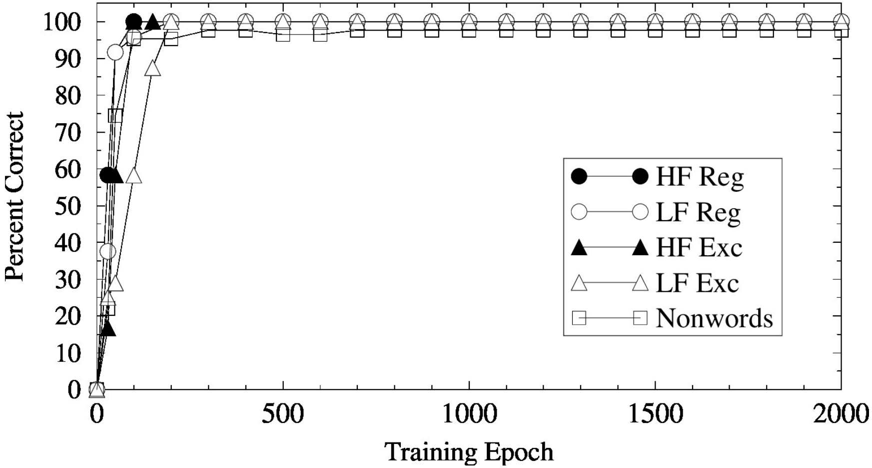
Simulation of surface dyslexia

- Feedforward network with weight decay
- Contribution of semantics approximated by external correct input to phoneme units that increases gradually and is frequency-sensitive

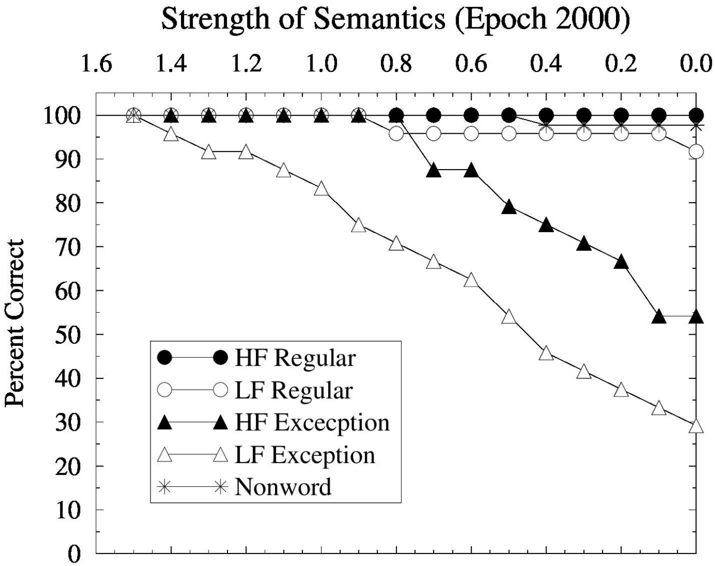




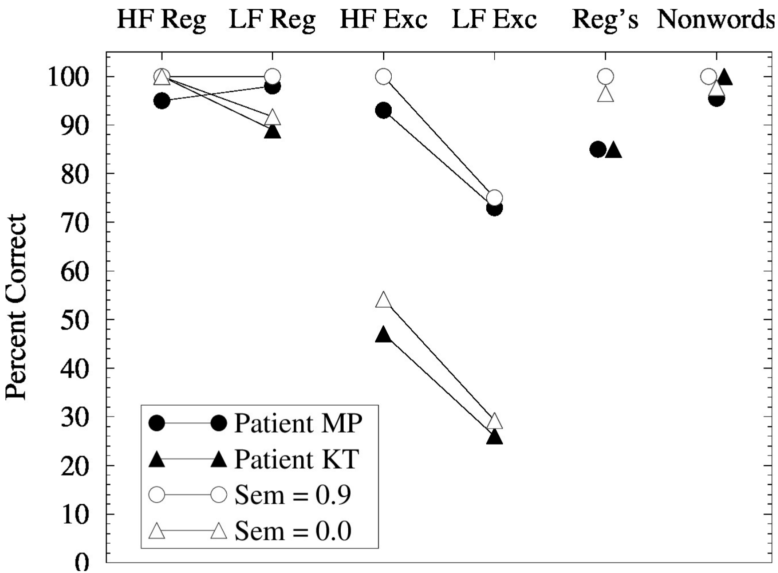
Overt reading performance



Effect of progressive semantic deterioration



Surface dyslexia: Individual patients (MP and KT)



Semantic impairment without surface dyslexia?

DRN (Cipolotti & Warrington, 1995); scientist with semantic dementia

- LF exceptions: 95% reading, 29% generating definitions

DC (Lambon Ralph et al., 1995); left school at 14, Alzheimer's dementia

- LF exceptions: 95% reading, 31% generating definitions

EM (Blazely, Coltheart, & Casey, 2005); secretary with semantic dementia

- 98% reading; 34% picture naming

Not due simply to severity of semantic impairment

- Other equally anomic semantic dementia patients exhibit surface dyslexia

GC (Patterson et al., 1994)	45% picture naming	38% LF Exc reading
PC (Blazely et al., 2005)	29% picture naming	49% LF Exc reading

Distribution of surface dyslexia among semantically impaired patients

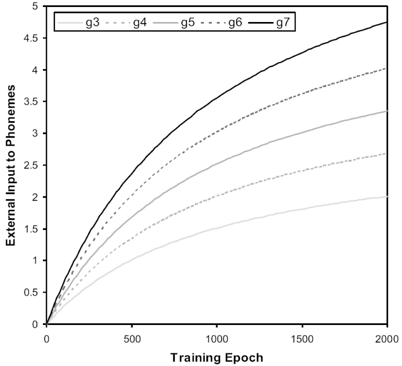
(Woollams, Lambon Ralph, Plaut, & Patterson, 2007)

Patients

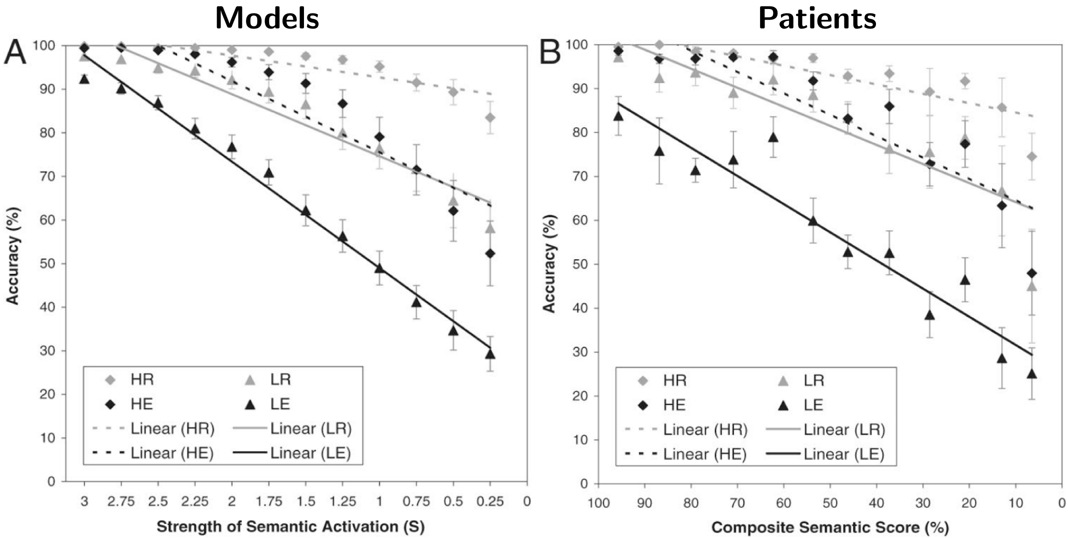
- 51 semantic dementia patients; 100 total testing sessions
- **Word reading** on Patterson and Hodges (1992) "surface" list
- **Composite semantic score** derived from performance on picture naming and spoken word-picture matching

Models

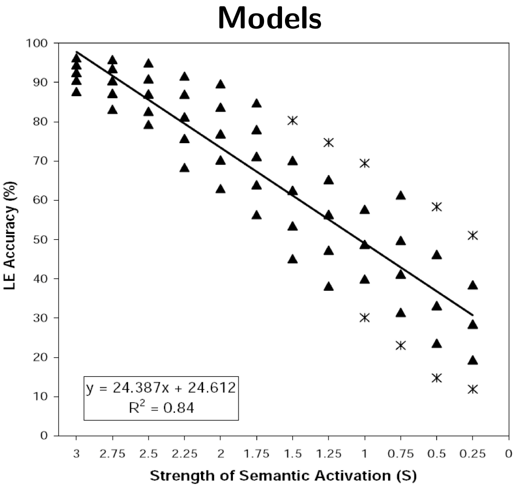
- Trained replications of Plaut et al. (1996) simulation varying only *semantic strength* ($g = 3$ to 7; original simulation used $g = 5$)
- Semantic "lesions" make semantic support for phonology *weaker* and *more noisy*

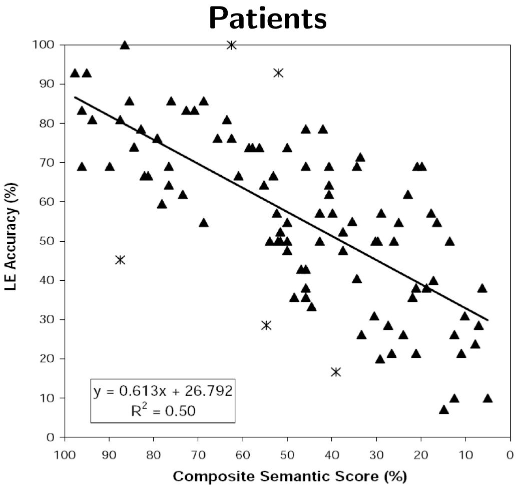


Reading accuracy as a function of semantic impairment

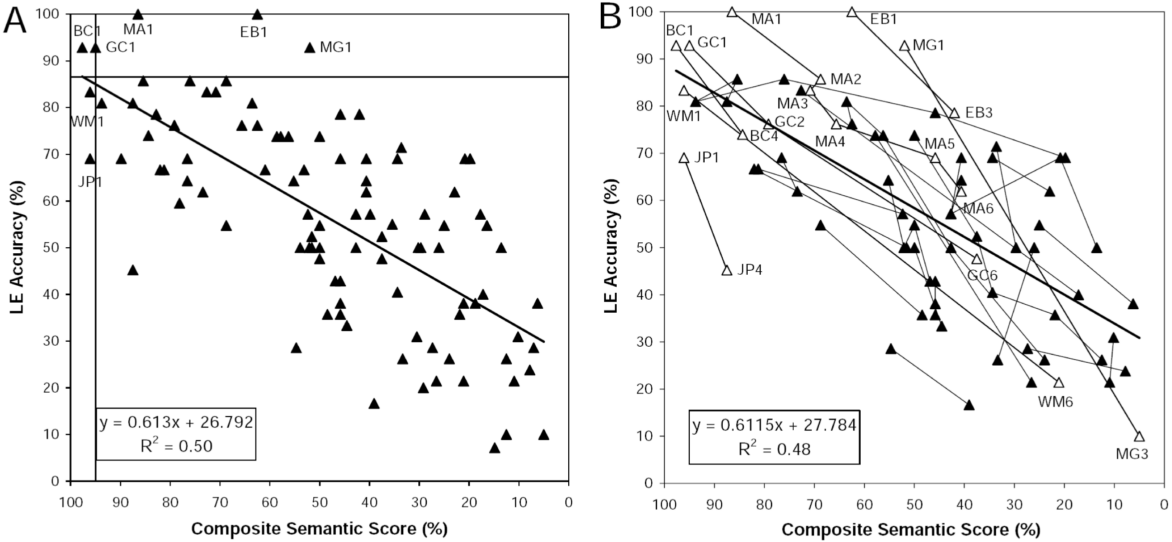


Low-frequency exception words





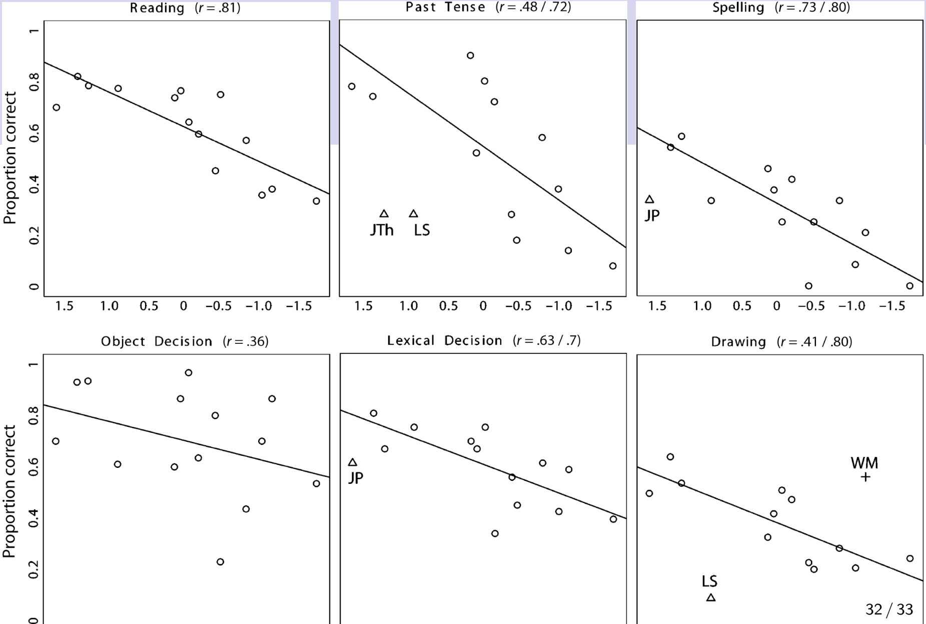
Outliers (PatientsPatients; longitudinal observations connected by lines)



Concomitant deficits

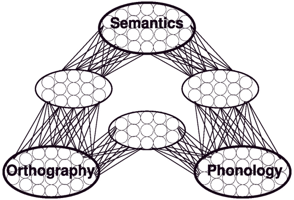
(Patterson et al., 2006)

Semantic dementia patients are impaired on "exceptions" in wide range of tasks



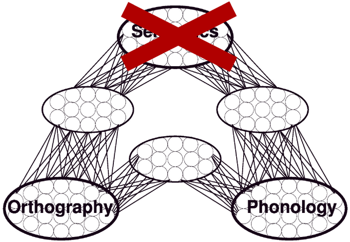
Triangle model of word reading

- Distributed representations for orthography, phonology, and semantics interact in processing words and nonwords
- Separate semantic and phonological pathways, but entire system participates in processing all types of items



Surface dyslexia

- Normal pseudoword reading
- Regularize exception words



Phonological/deep dyslexia

- Relatively intact word reading
- Very poor pseudoword reading