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On the Functional Architecture of Language and Reading: Trade-Offs Between Biological Preparation and Cultural Engineering

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The enduring legacy of Michael Posner's research derives from a set of ideas that have come to occupy center stage in understanding the human mind, its intellectual capacities, and how those capacities are supported by the brain. Posner was instrumental in developing these ideas into their modern form, and he has applied them with a power and energy matched by few other investigators of human cognition. I begin by describing these ideas. Then I review and try to integrate a wide range of studies of language and reading using these ideas as a guiding framework.

Mental Operations

The first idea is that perceiving, thinking, and acting can be understood as organized sequences of mental operations (Carr, 1984, 1986; Carr & Pollatsek, 1985; Carr, Pollatsek, & Posner, 1981; Posner, 1973, 1985). A mental operation takes input of a particular type and transforms it into output of a particular type, communicating the output to other mental operations that can use it as input.

Inputs and outputs are internal representations of information—sensory information from the outside world, retrieved memories of past experience, thoughts, and commands that move the muscles to produce actions. Each mental operation relies on a specialized knowledge base that defines and enables it to implement the mapping between inputs and outputs that is the operation's speciality. Different mental operations perform different information-processing jobs. To perform a task, one must pick and choose from the available repertoire of mental operations, treating them as building blocks from which to compose an organized sequence of operations that, if executed correctly, will get the task done. If a task requires a transformation of input to output that is not part of the currently available repertoire, then a new mental operation must be learned. As I show later, adding new mental operations to the capabilities of the visual and language systems is absolutely crucial to learning to read.

Formal models have simulated mental operations in a variety of ways. Some modelers have instantiated mental operations as algebraic interactions between feature vectors (Hintzman, 1988; Metcalfe, 1991, 1997), some as production systems (Anderson, 1983; Newell, 1990), and some as connectionist networks of varying grain size, ranging from localist networks in which each output node corresponds in one-to-one fashion with one of the representations that the operation is capable of activating (Besner, 1999; Collins & Loftus, 1975; Morton, 1969) to fully distributed parallel processing in which outputs are patterns of activation across large numbers of small feature-like components (Masson, 1999; O'Reilly & Munakata, 2000; Plaut, 1999). A few models—including some that are successful in modeling language and reading—are hybrid systems with multiple grain sizes or multiple types of representation and computation (Coltheart, Rastle, Perry, Landon, & Ziegler, 2001; Dell, Burger, & Svec, 1997; Dell & O'Seaghdha, 1994; Zorzi, Houghton, & Butterworth, 1998).

These variations in modeling format elicit intense debate among their devotees (for an interesting analysis of the relative success of these various formats, see Simon & Kaplan, 1989; for one kind of discussion of the partisan debate, see Carr, 1999). The goal at present, however, is not to decide among concrete formalisms, but to focus on what is common across them. In all cases, inputs that have already been activated are systematically transformed into outputs that constitute newly activated information in the mind. This alchemist's trick of creating new information from old is the key to achieving goal-directed task performance. To reiterate, people perform tasks by piecing together and implementing a sequence of mental operations that takes them from the initial stimulus situation or starting information to the end state that is the goal of the task. This end state may be a retrieved memory, a thought, or an action. The first idea, then, is that tasks are performed via an organized sequence of mental operations.

Attention

The second idea is that there are control processes to oversee the assembly and execution of an organized sequence of mental operations, thereby adding the notion of attention to the analysis and understanding of cognitive processes (Posner, 1973, 1985; Posner & Petersen, 1990; Posner & Raichle, 1994). Sequences of mental operations are governed by attentional processes that moderate overall arousal, selection, and maintenance of goals to be pursued; selection of perceptual inputs for detailed processing; short-term maintenance of activated representations that are needed as intermediate products; computation of decisions; and selection and execution of actions. These attentional processes moderate the flow of information among the information-transforming mental operations needed for a goal-directed task, and they work to coordinate the pursuit of multiple goals (and hence multiple streams of information-transforming operations) that might compete with one another in complex task environments.

Empirically, these various functions of attention have been pursued somewhat independently (e.g., see Yantis, 2000, for a review of selection of inputs for further processing, and Pashler, 2000, for a review of coordination of multiple tasks). Theoretically, however, they have been treated as interrelated and interacting components of an attention system (Baddeley, 2001; Carr, 1979, 1992; Carr & Bacharach, 1976; Meyer & Kieras, 1997; Pashler, 1997; Posner & Petersen, 1990; Posner & Raichle, 1994; Shallice, 1988). Thus the mechanisms of attention stand separate from the sequence of mental operations that they control. Interactions between the mechanisms of attention and the assembled sequence of component mental operations produce execution of task performance in real time.

Practice Makes Perfect: Expertise, Automaticity, and the Acquisition of Skill

The two ideas described so far are that cognition is achieved by organized sequences of mental operations assembled and governed by mechanisms of attention. A third idea stimulated by Posner is that the level of involvement of the various mechanisms of attention in task performance is not a constant. The need for attentional governance varies with instruction, practice, and the resulting level of task-relevant knowledge, expertise, and automaticity. The more one knows about a task, the more likely the task is to be performed correctly via an effective and efficient sequence of mental operations. The more a sequence of mental operations has been performed, (a) the more likely it is to be stored in memory as a directly activatable program or procedure (Anderson, 1993; Fitts & Posner, 1967; Keele & Summers, 1976; Posner & Snyder, 1975); (b) the larger is the collection of episodic memories or instances of its past performance that can be retrieved to help guide its current performance (Logan, 1988); and (c) the more likely are some or all of the required representations and component mental operations to be primed (that is, already partially activated) by recent experience (Bock, 1995; Carr, McCauley, Sperber, & Parmelee, 1982; Dagenbach, Carr, & Wilhelmsen, 1989; Neely, 1991; Posner & Snyder, 1975; Sudevan & Taylor, 1987). Knowledge and practice turn a novice's initial rough attempts at a task into the fluently executable skill of the expert.

How does this happen? Fluent execution is supported by a shift away from close attentional control. Via the three processes named above—proceduralization, amassing of episodic instances, and priming—practice makes performance of a task more automatic and reduces its burden on the mechanisms of attention. Sequences of mental operations actively constructed for the first time and held together to support a novel task draw the most heavily on the mechanisms of attention and are the most difficult to perform accurately and fluently. The difficulty posed by a novel task is especially great when instruction is minimal (so that the performer is not sure what mental operations to try), and when attention is distracted by irrelevant stimuli or spread thin by multiple task demands (so that the performer's ability to oversee the novel sequence of operations is at risk).

Thus instruction and practice are important factors in the relation between attention and mental operations and in the level of expertise a person exhibits at a particular task. Instruction facilitates learning an effective and efficient sequence of mental operations for the task's performance (Carr, 1984; Crossman, 1959; Fitts & Posner, 1967; Proctor & Dutta, 1995). Practice gradually frees performance of that sequence from the need for constant step-by-step monitoring by the attention system (Beilock, Carr, MacMahon, & Starkes, 2002; Beilock, Weirenga, & Carr, 2002; Brown & Carr, 1989; Carr, 1992; Fitts & Posner, 1967; Logan, 1988; Schneider & Shiffrin, 1977; Sieroff & Posner, 1988). Together, instruction and practice produce learning, and learning results in more fluent and less attention-demanding performance—that is, greater automaticity.

Enter Biology Versus Culture

At this point, with the focus on learning and automaticity, the underlying genetic substrate of the human being as a biological organism becomes critically important to understanding differences among tasks in how easy they are to learn and how frequently people who try to learn them end up failing. To a first approximation, there are two major support systems for skill acquisition: biological preparation and cultural engineering. Biology prepares people to gravitate toward, attempt, and become skilled at some task performances quite readily, giving those tasks a head start on learning and automatization. It is as if those tasks, or at least their rudiments in the form of a plan or blueprint on which to build, already exist in a dormant form in the nervous system and are just waiting to be triggered. But people are creative creatures, constantly inventing new tasks for themselves, turning these novel tasks into fluent skills through practice, and spreading these new skills to others through social interaction and various acts of instruction. Instruction can be formal, as in the school classroom, or it can happen less formally during interactions between parent and child, tutor and tutee, friend and friend.

People have been learning skills such as walking and running; or recognizing, reaching for, grasping, and throwing objects; or speaking and listening, for a long time—more than enough time for the foundations of these skills to get built into our biology. Other skills, however, such as reading and writing, have only been around for a few thousand years—not much time for biological adaptation to provide a lot of help. Nevertheless reading and writing have become central to living an informed, rewarding, and successful life in most cultures. Still other skills, such as chess, calculus, golf, basketball, automobile repair, commodity futures trading, and computer programming are even newer and are even less likely to enjoy the benefits of a heavily prepared biological foundation specific to that skill.

The invention of new tasks, the social transmission that spreads them, and the societal adoption that makes some of them necessary to life success force people to go far beyond biological preparation, gaining access to and control over biologically provided resources and harnessing them to the needs of the new task (Rozin, 1976). People must work hard to master complicated sequences of difficult mental operations that nature never imagined and hence did not build into the biological repertoire of prepared task performances. Culturally engineered tasks place greater burdens on attentional resources; require more direct, systematic, and intensive instructional support; and show greater individual variation in achieved skill level compared to biologically prepared tasks. In the theoretical world of cognitive psychology and cognitive neuroscience, the difference between biologically prepared and culturally engineered tasks is extremely interesting. It opens a unique window into the particular properties, strengths, and weaknesses of the human information processing machinery and how biology and experience combine to propel its development. In the practical world of people's everyday lives, the difference is important—we must take it into account and learn to manage it so that societally valued culturally engineered tasks can be mastered as closely as possible to the level of expertise that is more easily and universally achieved with biologically prepared tasks.

Reading as a Test Case

Reading is a prime example of a culturally engineered skill—a "skill of the artificial," as Simon (1981) might have called it. Because reading bears a close structural and functional relationship to a parent skill that is heavily biologically prepared—spoken language—it can serve extremely well as a model system for comparing and constrasting cultural engineering and biological preparation as foundations of skill acquisition. Furthermore, the answers gained by the study of reading clearly *matter*. Reading is at the top of the list of biologically unprepared but practically useful skills to be acquired if one wants to function well in modern societies. Most societies around the world value reading, most jobs require it in one way or another, and most governments spend large amounts of money trying to teach it to as many citizens as possible.

Despite the money and effort expended, individual variation in learning to read is high, even in a native language whose spoken form has already been mastered, and a substantial number of people fare so poorly at learning to read that they get labeled dyslexic, meaning that they tried hard to learn to read but they could not. These properties contrast strongly with learning the native spoken language on which reading is built, where individual variation in achieved competence is smaller and far fewer people fail to reach reasonably proficient standards of performance (Caplan, Carr, Gould, & Martin, 1999; Gleitman & Rozin, 1977; Liberman, 1995; Rozin & Gleitman, 1977). It would be good to know how these properties of reading should be understood theoretically, and how they can be dealt with instructionally.

Determining the Brain's Problem in Learning to Read

What specific modifications must be made to the natural information processing capacities of the human brain to create a reader out of a normally developing child who is equipped with the usual complement of biologically prepared cognitive and linguistic capacities?

The Cognitive and Linguistic Status of the Prereading Child

Around the world, children commonly enter school-based reading instruction somewhere between ages 5 and 8. By this time, they are already accomplished visual and linguistic information processors. Before they know how to read, almost all children know how to perceive, understand, and act on the visually-perceptible world, and how to listen, speak, and engage in conversation. Although 5- to 8-year-old children may not be at adult levels in the speed, accuracy, and complexity of these skills, or in their freedom from distractibility and attentional limitations when trying to exercise them, they are nevertheless quite impressive in absolute terms. They have come a long way since infancy.

Despite their visual, motor, and linguistic accomplishments, however, prereading children do not know how to read. Reading requires that a new set of skills be developed—treating visual stimuli as words comprising texts that refer to and describe objects, scenes, and events in symbolic form, rather than presenting visual evidence of objects, scenes, and events directly to the machinery of visual perception. Prereading children possess a well-established language system that is biologically prepared to listen to linguistic input collected by the ears—but it does not know how to look at linguistic input collected by the eyes. Furthermore, prereading children possess a well-established visual system that is biologically prepared to construct object representations and piece them together into scenes and track them over time to construct events—but it does not know how to construct word representations and string them together into sentences and texts. The language system is not a visual system, and the visual system is not a language system.

Thus the primary problem to be solved in turning a prereader into a beginning reader is to establish an effective interface between vision and language. Considerable evidence from a wide variety of sources indicates that this interface is established at the level of the word, and that learning to analyze and recognize visually presented words *as* linguistic entities rather than as visual objects is the difficult but indispensable task facing the prereader.

Recognizing Words as Linguistic Entities Is the Foundation of Reading Skill

To learn to read, the brain must make a choice. Is a printed word just another visual object with parts? Are these objects laid out in space like visual scenes? Do the objects move around as causal events unfold? If so, the job is simple—the visual system can create structural descriptions of the parts and how they fit together and pass these structural descriptions on to inferotemporal and parahippocampal cortex, where they are identified as members of object categories and placed relative to one another in environmental space, just like always. These structural descriptions will make contact with visual associative memory. Particular structural descriptions will retrieve object-specific, scene-specific, and event-specific knowledge about identity, category memberships, functions, affordances, and past experiences.

Alternatively, maybe a word is not just another object. Maybe it needs to be treated as an instance of language (whatever that is—keep in mind that in the prereading child, the visual system is not a language system). If a word is an instance of language instead of an object, then the visual system needs to learn some new skills (for reviews, see Adams, 1990; Carr & Posner, 1995; Rieben & Perfetti, 1991; Rozin & Gleitman, 1977).

These skills still involve visual shapes, but they are no longer three-dimensional parts connected together in three-dimensional space to form objects, or even two-dimensional pictures representing such three-dimensional configurations. They are two-dimensional shapes organized into two-dimensional spatial arrays, with linear order crucial in both dimensions. In alphabetic writing systems such as English, Welsh, Spanish, Italian, Finnish, Russian, Serbo-Croatian, Hebrew, or Arabic, the shapes are letters and clusters of letters called *graphemes,* which are strung together in systematic, highly structured sequences to spell words.

Some sequences of graphemes are common, others are rarer but perfectly acceptable, and others are illegal—they simply do not occur in the spelling system of the written language. These constraints on graphemic order and combination are referred to as the orthographic structure of the writing system. Every skilled reader is sensitive to orthographic structure. If I ask you, as a skilled reader of English, to say which of the following sequences of letters—bluck, cbptklm, pasp, ckik—follows the acceptable patterns of English spelling and hence could conceivably be the spelling of a word, you would have no trouble deciding that the correct answer is the first string "bluck" and the third string "pasp." These so-called pseudowords possess all the right properties to be part of the English lexicon—they just do not happen to have been chosen to be words, at least so far in the development of the language. The second string "cbptklm" and the fourth "ckik" are not acceptable as English spellings. Such a decision can be reached intuitively, relying on knowledge that is basically implicit (those strings just do not look right) or explicitly, relying on knowledge of varying degrees of precision and certainty that can be formulated for report (there are no vowels in "cbptklm," and all English spellings have vowels in them; and "ck" corresponds to a sound that can occur at the beginning of a word, but the spelling "ck" itself can only occur at the end of a word, so "ckik" cannot be an English spelling). One might even rely on rules of spelling learned in a formal way ("i before e except after c" being one that many people can recite, although it does not help with this set of examples).

Note that some of the knowledge needed to make these orthographic judgments is specifically visual (in English, "ck" never appears as the first grapheme of a word, although it is perfectably acceptable and, in fact, quite common in the middle as in "pickle" or at the end as in "kick"). Much of our orthographic knowledge, however, seems to correspond to or even depend on knowledge of patterns of pronunciation ("bluck" and "pasp" are acceptable because they can be pronounced in a way that sounds like English). This realization points to the most profound fact about the problem that reading poses for the brain: the new skills that the visual system must learn are not just visual. They also involve phonemes and how phonemes are strung together and integrated to make a spoken word. This is because the graphemes are symbols that refer to and map onto the pronunciations of the spoken language. The ultimate goal of the new skills that the visual system must learn involves phonological recoding—the set of mental operations that transform visual representations coded in terms of sequences of graphemes into phonological representations coded in terms of sequences of phonemes. Given that phonological recoding relies on new mental operations not already in the prereader's repertoire, we can expect that learning them will be attention demanding, and hence that both the conditions of instruction and the conditions under which the skills must be deployed will prove to be crucial. Simpler conditions, less cluttered conditions will be better, and conditions crafted specifically to focus on and highlight just what needs to be learned will be better.

Is this argument correct? One might wonder at the outset just what is the evidence that underlies the claim that learning to recognize visual words as linguistic entities is the foundation of the reading process, and that phonological recoding is a crucial part of this foundation?

Evidence From Eye Movements While Reading Text

For approximately 100 years, perceptual and cognitive scientists have been developing more and more accurate methods of measuring the pattern of eye movements that takes place during reading. This pattern consists of a sequence of fixations, each bringing foveal vision to bear on a few letters of text—six to eight or so at a time can actually be resolved to the point of explicit identification in normally sized text at normally chosen reading distances, and perhaps twice that number might influence processing in some fashion, taking into account implicit effects from letters that have been partially processed but not explicitly recognized. Fixations last for 150 to 400 ms or thereabouts, with the average fixation lasting 200 to 250 ms. Each fixation is followed by a ballistic saccade that moves the direction of gaze to the next point of fixation. Most of these saccades move forward in the text, averaging about eight letters or so, but 10% to 15% are regressions that take the eyes back to a region of text that has been fixated before.

Measuring eye movements has amassed a large body of knowledge about the spatial pattern and time course of gathering information from text (for reviews, see Carr, 1986; Just & Carpenter, 1987; Rayner, 1999; Rayner & Pollatsek, 1989). Judging from where and when the eyes are aimed, children read text word by word. On average, elementary-school-aged readers look at every content word, usually more than once. Highly literate college-aged adults do much the same, still looking at almost every content word, and spending two or more fixations on longer words. Highly literate adults skip most function words and may skip some familiar high-frequency words that are predictable from context, with skipping more likely for shorter words than for longer ones. But most content words—nouns, verbs, modifiers—receive at least one fixation. Thus words are important units of information acquisition, even for readers who are skilled and experienced.

Furthermore, both the overall length and the internal orthographic structure of a word influence where within that word the eye is most likely to fixate. The preferred landing position for the initial fixation on a word of fewer than about seven or eight letters is just to the left of the word's center. The initial landing position shifts further into the word if the initial graphemes of the word are a high-frequency combination that appears frequently in the written language and hence has been encountered many times in the past. The initial landing position shifts closer to the beginning of the word if the initial graphemes are a rarer combination with which the reader is not as experienced. These shifts happen as a function of graphemic frequency per se, with the overall frequency of the words controlled. Such sensitivity to orthographic structure makes it clear that words are not encoded as visual wholes, or at least not solely in such terms, but instead are encoded in terms of sequences of graphemes. Why should this be? The hypothesized answer is that such a coding strategy facilitates contact with the phonological representations of the language system and hence facilitates establishing the vision–language interface that supports phonological recoding.

Evidence From Word-Processing Tasks

Measuring eye movements tells researchers where information is being gathered from text, and how long it takes to get it. Measuring the speed and accuracy of making specific judgments about letter strings with particular properties can tell us about the details of how a letter string is encoded and evaluated. Gibson, Osser, and Pick (1963) asked first and third graders to report what they could see from brief tachistoscopic presentations of three different kinds of letter strings: real words, pseudowords, and random strings. The difference between words and pseudowords indexes the impact of familiarity and meaning over and above the impact of orthographic structure and pronounceability. The difference between pseudowords and random strings indexes the impact of orthographic structure and pronounceability per se. To a rough first approximation, one might think of the word–pseudoword difference as pointing toward recognizing words as familiar objects, whereas the pseudoword–random string difference points toward recognizing words as linguistic entities. First graders showed an advantage for three- and five-letter words over both pseudowords and random strings, demonstrating sensitivity to familiarity and meaning. They showed a smaller advantage of three-letter pseudowords over random strings, but no advantage of five-letter pseudowords. Thus in this demanding task, first graders showed an ability to treat words as objects and the beginnings of a possibly emerging ability to treat words as linguistic entities. By third grade, the advantage for pseudowords over random strings was there for the longer stimuli as well, although with the five-letter stimuli, words were still recognized better than pseudowords. One might conclude that mastery of orthographic and phonological structure is a lagging consequence of reading instruction and experience—beginning readers first treat letter strings as individual objects, gradually acquiring the structural knowledge needed to treat them as linguistic entities.

Similar developmental trends were observed by McCandliss, Posner, and Givon (1997) in studies of young adults learning an artificial writing system with an alphabetic orthography, and by Givon, Yang, and Gernsbacher (1990) in a study of young adults learning to read Spanish as a second language. Haynes and Carr (1990) found that the pseudoword advantage over random strings in visual same–different matching—a task especially sensitive to visual encoding (Carr, Pollatsek, & Posner, 1981)—predicted not only reading comprehension but the ability to learn new word meanings from context among Taiwanese young adults learning to read English as a second language. These results indicate that the gradual education of the visual system about orthographic structure and how to map orthography onto phonology and meaning discovered by Gibson and colleagues is in fact an accompaniment to learning to read a new writing system regardless of age and past experience with other writing systems, not a developmentally driven phenomenon limited to young children learning to read for the first time. For an expanded version of this argument, see Posner and McCandliss (1999).

Evidence From Individual Differences in Semantic Priming of Oral Reading

I now turn more specifically to evidence involving the activation of word meaning and its relation to comprehension, but still in the context of recognizing individual words. Perfetti, Goldman, and Hogaboam (1979) compared good and poor fifth-grade readers in two tasks. One was a cloze task in which content words were deleted from sentences and children were asked to fill in the blanks—to guess the words that had been deleted. Each deleted word was semantically consistent with the sentence and moderately predictable from it, as determined by preacquired norms. The cloze task provided a measure of how well each child understood the sentence and could use that understanding to predict an upcoming word. The other task was timed oral reading of intact versions of the same sentences. Some of the sentences were completed with the semantically consistent, predictable content word that had been deleted in the cloze task, whereas other sentences were completed with a semantically inconsistent and unpredictable word. Pronunciation latencies for these two kinds of target words were compared to provide a measure of semantic priming—how much did each child make use of and rely on or benefit from semantic consistency and predictability during online reading of intact text?

As one might expect, good readers more often filled in the blanks in the cloze task with words that were semantically and syntactically appropriate, completing the sentence in a sensible and grammatically correct manner. More of the good readers' completions were, in fact, just the word that had been deleted—and hence would be the semantically consistent target word if that sentence were read in its intact form. Thus good readers understood the sentences better and were more capable of using their understanding to predict upcoming words. These results were not surprising.

One might also expect that the greater comprehension and predictive prowess of good readers would translate into greater semantic priming effects.

However, this did not happen. Good readers showed smaller semantic priming effects, in both absolute and percentage terms. In particular, good readers slowed down much less and made many fewer errors on the inconsistent, unpredictable words than did the poor readers. The poor readers were significantly hampered by inconsistent context. Their errors were often words that were semantically consistent with the context, showing a reliance on context to help infer upcoming words that good readers did not show.

Perfetti and colleagues (1979) argued from these results that although good readers can use context to make guesses about upcoming words, as indicated by their superior cloze performance, they do not need to do so during online, real-time reading. Their stimulus-driven word recognition skills are fast and accurate enough to take priority. It is the poor readers, whose word recognition skills are weaker, who rely on context for help. Even though the poor readers' grasp of the context is not always very good, they try to apply what grasp they have in an attempt to compensate for word recognition skills that are not up to the job on their own—and, as demonstrated by their errors, this reliance on context can backfire.

Thus in a task that specifically involves phonological recoding—the oral reading or "naming" task—better readers are better at recognizing words based only on the visual stimulus information from the individual word itself, independently of cues from context. Biemiller (1970) observed from the nature of errors in oral reading that normally developing readers pass through a stage of relying on context but pass out of it as their stimulus-driven word recognition skills consolidate and solidify. Beyond the first few years of reading instruction and practice, it is the mark of the poor reader, not the good reader, to rely on contextual cues rather than stimulus-driven word recognition. Stanovich (1980) has extended the argument for compensatory use of context by poor readers to a much wider domain of reading tasks.

Evidence From Individual Differences in Comprehension and What Predicts Them

Oral reading is an important real-life skill—ask any parent who reads *Good Night, Moon* to a 3-year-old, or any president who reads from the teleprompter to give a speech about a war. Nevertheless, one might prefer evidence from comprehension measured directly rather than inferred from semantic priming in oral reading, on grounds that if one must choose one or the other, understanding what one reads is more useful than being able to read it aloud fluently.

There is now a large body of evidence demonstrating a developmentally extended hierarchy of prediction among measures of reading and reading-related abilities. Preschoolers' letter knowledge (being able to name the letters of the alphabet) and phonological awareness (being able to judge whether two spoken words rhyme, to break syllables apart and exchange their initial sounds, to play word games involving phoneme deletion and substitution such as "pig latin," and so on) predict their later success in school phonics activities, including learning the acceptable spelling patterns that constitute orthographic structure and learning to work out the correct pronunciations of printed pseudowords—a behavioral manifestation of phonological recoding. Success in phonics activities and pronouncing printed pseudowords predict correct recognition of printed real words. Finally, pronunciation of pseudowords and recognition of real words predict reading comprehension. For reviews of this evidence, see Adams (1990); Manis, Szeszulski, Holt, and Graves (1990); Rieben and Perfetti (1991); and Goswami (1999). Furthermore, pronunciation of pseudowords and recognition of real words remain independent predictors of reading comprehension even among highly literate college students, and even after controlling for a wide variety of other potentially important predictors of reading comprehension, such as IQ, world knowledge, and spoken language comprehension (Cunningham, Stanovich, & Wilson, 1990). Thus the predictive power of mastering orthographic structure, phonological structure, and the mental operations of phonological recoding extends beyond oral reading per se. Learning to recognize words as linguistic entities does appear to be the foundation of the reading process.

Evidence From the Impact of Instruction

It is by now extremely well established empirically that beginning reading curricula should include a regimen of phonics activities—specific instruction and practice aimed at becoming acquainted with orthographic structure, phonological structure, and phonological recoding. Such curricula produce greater achievement on average during the first two to four years of formal reading instruction than do curricula that deemphasize or exclude phonics activities (Adams, 1990; Chall, 1967, 1983; Evans & Carr, 1985; National Reading Panel, 2000; Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2002). Furthermore, as I have just shown, the skills of word recognition acquired through such activities predict subsequent reading success, including reading comprehension.

School instruction does not begin from nothing. There is a growing body of evidence on the nature and impact of parent-child book-reading activities, focusing on the preschool years. These activities provide various kinds of reading experience and informal reading instruction, laying the groundwork for the more formal instruction that lies ahead in school. Evans and colleagues (Evans, Bell, Mansell, & Shaw, 2001; Evans, Moretti, Shaw, & Fox, 2003) videotaped parents reading books with their preschool children, applying an observational coding scheme to assign the observed activities to categories. The focus was on situations in which the children were trying to do at least some of the reading.

They have found that parents differ substantially along three dimensions: (a) their emphasis on overall comprehension, making sure that their children understood the message the narrative was trying to convey; (b) their emphasis on using context to guess words, encouraging their children to pay attention to pictures and other cues to overall meaning to figure out what a particular unknown word might be; and (c) their emphasis on having fun, using book-reading as a tool to create positive social interaction. Where parents stand along these dimensions can be predicted from their beliefs about what reading is for and how it is done, which Evans and colleagues measured in separate questionnaires.

More interesting were two things parents do that are not predicted by their beliefs. First, parents tend not to let mistakes pass. If a child gets a word wrong, the parent is likely to correct the mistake, either supplying the correct word or leading the child through another attempt at its identification. This is quite consistent with the literature on skill acquisition—learning proceeds more rapidly with feedback about success (for a review, see Proctor & Dutta, 1995).

Second, all parents engage to some degree or another in phonics instruction, again regardless of expressed beliefs about the nature of reading. They call attention to letters and how those letters might be translated into pronunciations, make suggestions based on similarity of spelling or sound, and in other ways focus on how the writing system encodes phonology and maps onto spoken words. This is quite consistent with the literature on reading instruction as already discussed—reading progress is facilitated by a regimen of phonics activities. Furthermore, the amount of phonics-like instruction during preschool parent–child book-reading correlates positively with reading progress once school instruction begins. Thus it would appear that the parents studied by Evans and colleagues were to greater or lesser degree intuitive scientists, seeming naturally to grasp the truths that have been so hard-won in the literature on reading instruction and implementing them in varying amounts in their interactions with their children. The amounts predicted how much good is done. A regimen of phonics instruction, combined with feedback on success at recognizing words and understanding the sentences they make up, facilitates reading development.

Third, there is the issue of how a child's own relative skill at spoken language influences his or her progress at learning to read. Although variation in spoken language skill is less than that observed in reading, there is some. Does it make a difference in learning to read?

One way to address this question is to specifically seek out children with exceptionally strong spoken language skills. Crain-Thoreson and Dale (1992) selected children for verbal precocity at age 20 months and followed them longitudinally. Although they remained verbally advanced relative to other children, they did not show more rapid reading development by virtue of their greater language skills. What did predict emerging literacy was degree of exposure to letter names and sounds, and other kinds of phonics-related activities, in the home. This study suggests in yet another way that strong spoken language skills are not enough to become literate. Specific instruction in what I have been calling the new set of skills that the brain needs to learn is a required ingredient.

A second way to address the question of how spoken language skill relates to reading progress is to investigate the impact of different kinds of formal reading instruction. Suppose that the relation between spoken language skill and reading progress is indeed dependent on and mediated by instructional support for educating the visual system about orthography and establishing a visual–phonological interface with the language system. If so, then beginning-reading curricula that emphasize such phonics-related activities should be more conducive to helping children bring to bear their existing spoken language skills in making reading progress.

To find out, Evans and Carr (1985) compared two curricula in a naturalistic study of classroom activities in a large urban school system. One was a curriculum whose reading instruction consisted of phonics, guided instruction at learning word meanings from context, and guided instruction at writing and spelling—activities aimed at treating words as linguistic entities and providing feedback about success. The other was a radical version of the so-called whole language curriculum. Children made up stories and told them to the teacher, who wrote the stories down. These stories became the children's reading texts, and the words in the stories were put on flash cards to teach whole-word visual recognition—an activity that treats words as visual objects.

In the phonics and guided instruction curriculum, measures of spoken language competence including sentence complexity and mean length of utterance correlated positively with reading achievement measured at the end of the school year. However, in the whole language curriculum, despite its well-intentioned attempts to help children use their own preexisting language and personal interests as the basis for learning to read, the correlations were significantly negative. That is, children with stronger spoken language skills actually achieved less in learning to read than children with weaker spoken language skills. Evans and Carr concluded from this striking result that spoken language skills can mesh with and facilitate reading development—but only if explicit instruction is aimed at giving children the tools they need to take advantage of their spoken language. These tools involve educating the visual system about writing, and establishing an interface between visual knowledge of writing and linguistic knowledge of word forms and their internal structure—that is, the tools that allow a child to treat written words as linguistic entities rather than visual objects.

The Reading Wars

Although the scientific evidence is considerable (and in my view overwhelming in its breadth, consistency, and weight), the idea that learning to recognize printed words as linguistic entities is the foundation of reading skill is nevertheless a hotly debated proposition. Not everyone believes it, especially in educational circles, in which ideological and sociopolitical commitments about reading are strong. Such a valuable societal commodity as reading should engage people's commitments, and it should inspire passion in the public arena. However, commitment and passion should not displace the scientific evidence.

This debate as it plays out in the public arena is illustrated in a column by Norman Lockman (2003) of the *Wilmington News Journal,* which I came across in my local newspaper one morning while working on this chapter. The title was "Reading Is Too Vital for Games: Educators' Efforts to Ease Conflicts Hurt Neediest Kids." I quote Lockman because I believe he has gotten the instructional implications of the scientific evidence just right, and the more this happens the better it will be for the prospects of children learning to read.

Lockman begins with the premise that schools do children no favors if they adopt teaching methods that promote enjoyment and personal interest but do not establish the skill that is supposed to be taught. How can one argue with that? He goes on to say,

> I've always thought reading meant being able to pick up a piece of unfamiliar written material and decipher its contents in order to understand the thoughts (or instructions) of someone other than myself. It's the key to learning everything else.
>
> So what is the point of teaching a child to understand his own scribblings as means of learning to read? The educational progressives say it avoids "drill and kill," by which they mean avoiding the drudgery of learning the basics of written language by boring repetition.
>
> I think it comes down to hedging bets by teachers who do not want to be held responsible for the absolutes of achieving full literacy among children with no personal or parental understanding of its value and no motivation to acquire it. It's a pedagogical dodge.
>
> Learning to read is not easy. I can remember struggling with reading material that was frustrating to comprehend and resenting teachers who insisted that I do so. But I also remember feeling triumphant when it began to make sense.

Summing Up the Brain's Problem in Learning to Read

Several enhancements of brain functional organization must be achieved to get a nascent reading system up and operating. The visual system needs to be educated about writing—learning component symbols and the orthographic structure that characterizes how the symbols are combined into patterns of spelling. Word and pseudoword superiority effects in visually sensitive tasks such as same–different matching, search for target letters, and tachistoscopic report index the development of this capability. Word superiority effects indicate the initial lexical basis of this knowledge—the reader is learning the visual configuration of specific words as a start. Pseudoword superiority indicates broader learning and the consolidation and generalization of lexical knowledge into patterns of orthography. In addition, the phonological system must be made accessible at the level of syllabic structure—onsets and rimes—and, ideally, at the even more analytic level of the phoneme. Engagement in phonological awareness activities forges this level of accessibility, and successful performance of such activities provides behavioral evidence that it is being achieved. An interface needs to be established between the visual system and the phonological system, so that visual representations of orthography can map onto the language system's phonological representations of pronunciation and vice versa. Phonics activities and guided practice at sounding out pronounceable strings of letters—whether words or pseudowords—creates this interface, and success at pronouncing pseudowords provides behavioral evidence that it is being established. The more consistent the generalizable patterns and the fewer the exceptions to those patterns, the faster skills at treating printed words as rule-governed linguistic entities are established (Ellis &

Hooper, 2001). English, however, requires mastery of many exceptions, and progress is slower. These skills, in turn, predict success at higher levels of processing, including text comprehension, both in the short term among elementary school students and in the long term—even among college students.

The Neural Substrate of the Solution: What Does the Reading System Look Like Once the Vision–Language Interface Is Established?

Two major bodies of evidence address this question. One is evidence from trauma-induced brain damage; the other is evidence from neuroimaging.

Traumatic Dyslexia: Evidence From Lesion Damage

Three major types of trauma-induced dyslexia can be found consequent to specific brain damage (Banich, 1997; McCarthy & Warrington, 1990). Pure alexia harms the recognition of all types of words and pseudowords, essentially knocking out the reading system in all respects. Pure alexia most often results from damage to left extrastriate and anterior occipital visual cortex.

Surface dyslexia differentially harms the recognition and proper pronunciation of words with exceptional spelling-to-pronunciation mappings—words that violate the generalizable patterns that occur most frequently in the written language. Such exceptions include words such as "blood," "pint," "sword," "then," and "know." The errors produced in surface dyslexia tend to regularize these exception words, as if the ability has been lost to retrieve and apply word-specific lexical knowledge to override the central tendencies of the body of known patterns of phonological recoding. One way of thinking about surface dyslexia is that it constitutes relative loss of the ability to treat words as visual objects accompanied by the relative sparing of the ability to treat words as linguistic entities. Consistent with this way of thinking, surface dyslexia results from damage to inferior occipitotemporal cortex, anterior to the regions most often involved in pure alexia and further along in the ventral visual stream involved in object recognition and associative memory.

Finally, phonological dyslexia involves a complementary pattern to surface dyslexia. There is relative preservation of the ability to recognize and properly pronounce familiar words, whether consistent with the general patterns of spelling-to-pronunciation mapping or exceptional. What is differentially harmed is recognition and pronunciation of less frequent words, especially regular-consistent ones, and in particular, applying the generalizable patterns of spelling-to-pronunciation mapping to generate a reasonable pronunciation for a pseudoword or a real but unknown word. Phonological dyslexia looks like relative loss of the ability to treat words as linguistic entities accompanied by the relative sparing of the ability to treat words as visual objects. It most often results from damage in regions of occipitotemporal and occipitoparietal cortex anterior and superior to the regions involved in pure alexia.

This tripartite anatomy of trauma-induced dyslexia suggests that in learning to read, the brain does not make an all-or-none choice between treating words as objects or as linguistic entities. Opting for redundancy (as is often the case in biological systems), the brain pursues both possibilities. Visual word processing begins in extrastriate visual cortex, then diverges, with lexically-specific, associative-memory-based processing differentially supported by a ventral pathway into inferior temporal cortex and linguistic analysis of orthography and its mapping onto phonology differentially supported by a more dorsal pathway into superior temporal and inferior parietal cortex.

Evidence From Neuroimaging of the Normal Brain

The perils of drawing conclusions about normal functional organization from the consequences of brain damage are well known. However, the advent of neuroimaging—particularly positron emission tomography (PET) and functional magnetic resonance imaging (fMRI)—has enabled such conclusions to be treated as hypotheses that can be explored in the undamaged brains of normal readers.

OCCIPITAL ORTHOGRAPHIC PROCESSING: THE VISUAL WORD FORM SYSTEM. Warrington and Shallice (1980) were the first to hypothesize that pure alexia represents damage to an area of brain tissue specifically devoted to creating a visual representation of a printed word. At the same time, a large body of behavioral evidence had been accumulated from tasks known to emphasize visual rather than lexical-semantic, phonological, or articulatory processing, with the most diagnostic results coming from same–different matching of simultaneously-presented letter strings (Carr, Pollatsek, & Posner, 1981). This evidence converged on the hypothesis that the visual system "knows" the orthographic structure of the written language and uses that knowledge in constructing representations of words and word-like letter strings (Carr, Pollatsek, & Posner, 1981; Carr, Posner, Pollatsek, & Snyder, 1979; for additional reviews of the evidence, see Carr, 1986; Carr & Pollatsek, 1985; Henderson, 1982).

These two hypotheses—one anatomical, one computational—were brought together in the seminal PET imaging work of Petersen, Fox, Posner, Mintun, and Raichle (1989). These investigators found that blood flow in a region of left medial extrastriate cortex increased relative to a baseline fixation condition in a variety of tasks with visually presented words but not in tasks with auditorily presented words. Another crucial test of this region's properties was performed by Petersen, Fox, Snyder, and Raichle (1990). They found that not just words but also pseudowords activated left medial extrastriate cortex relative to a fixation baseline, but looking at random strings of letters did not.

Based on this evidence, Posner and Carr (1992) suggested that the occipital region, called the visual word form area by Warrington and Shallice (1980), is an orthographic encoding mechanism—a region of tissue that performs the mental operation of preparing a representation of letter identities and their order for letter strings with sufficient orthographic structure to be word candidates. These representations are shipped forward to inferotemporal, temporoparietal, and prefrontal cortex for lexical-semantic, phonological, and articulatory processing. Carr and Posner (1995) went further, arguing that the visual word form area constitutes a primary gateway from the visual system to the language system—the visual-system front end of the vision–language interface that must be established to ensure that a listener–speaker can become a competent reader.

Subsequent neuroimaging investigations have shifted the most likely anatomical locus for the visual word form area slightly in the anterior direction from the early results of Petersen and colleagues. The weight of evidence now suggests that orthographic encoding is most likely to be found in occipitotemporal fusiform gyrus, rather than extrastriate cortex, although there is some variability from person to person in how posterior in the visual system the region begins (see Cohen et al., 2000 and Polk & Farah, 2002, for reviews). Such individual variability is to be expected in neural systems, highlighting the need to examine the functional-anatomical data of each person rather than focusing only on averaged group data. Based on such analyses, it is now quite clear that this region of tissue can be found in most mature readers. It responds to visual but not auditory words (Dehaene, Le Clec'H, Poline, Le Bihan, & Cohen, 2002). It cares about the order in which letters occur and not just which letters are present (McCandliss, Bolger, & Schneider, 2000). It responds to pseudowords just about as vigorously (Dehaene, Naccache, et al., 2001; Polk & Farah, 2002) and on just about the same time-course (Ziegler, Besson, Jacobs, Nazir, & Carr, 1997) as it responds to words. Finally, it operates on what the cognitive literature on word recognition has called "abstract letter identities"—representations of letter identity that are independent of purely visual variation such as letter case or typefont (Besner, Coltheart, & Davelaar, 1984; Carr, Brown, & Charalambous, 1989)—rather than to visual familiarity per se. For example, Dehaene, Naccache, and colleagues (2001) and Polk and Farah (2002) both report that the left occipitotemporal region that responds approximately equivalently to words and pseudowords does so as strongly for aLtErNaTiNg-CaSe stimuli as for the visually much more familiar pure case stimuli standardly encountered in reading. From this finding Polk and Farah suggested that this brain region ought to be called the "abstract word form area" rather than the "visual word form area." This proposal is quite consistent with Carr and Posner's argument that this region of the visual system is an orthographic encoding mechanism capable of serving the "abstractionist" needs of spelling-to-pronunciation translation in particular and communication with the linguistic system more in general.

Temporal and Temporoparietal Phonological Processing Identifies Dyslexic Individuals. From anatomical and functional imaging data, Cohen and colleagues (2000) argue that the visual word form area is the first completely abstract, position-invariant encoding region in the ventral-stream sequence involved in word processing, and the last purely visual region. They argue also that its connectivity is both to further ventral-stream regions and more dorsally, to posterior temporal and temporoparietal regions, both left and right hemispheric.

This posterior temporal and temporoparietal connectivity, combined with the lesion evidence regarding phonological dyslexia already described, suggests that the rest of the vision–language interface crucial for phonological recoding lies in posterior temporal and temporoparietal cortex. To document a role for these regions in phonological processing related to reading ability, Temple and colleagues (2001) used fMRI to assess activation during a task that required rhyming judgments about pairs of letters. Relative to a baseline task that required visual same–different matching, Temple and colleagues found increased activation in left posterior superior temporal gyrus—the vicinity of Wernicke's area—in 10-year-old normal readers. This activation was absent in 10-year-old dyslexic readers. Shaywitz et al. (1998), using a task that required rhyme judgments about pseudowords as the phonological task and judgments of letter case as the visual baseline, found the same difference in left posterior superior temporal activation in a comparison of normal and dyslexic adults. Given the large body of evidence that Wernicke's area and adjacent tissue is heavily involved in a wide variety of language tasks involving phonology (for a review, see Binder & Price, 2001), the absence of activation in this area during phonological judgments is a clear indicator of a deficit in the preferred pathway for phonological processing among these dyslexic readers.

When a preferred pathway fails to develop, the brain often tries to find a compensatory strategy for getting the required processing accomplished. An fMRI investigation of the development of reading-related functional anatomy in normal and dyslexic children adds to the evidence for deficient occipital-temporoparietal development and also points toward a possible compensatory strategy. Shaywitz and colleagues (2002) found that poorer readers showed less activation overall both in occipital regions (the visual word form area) and in posterior superior temporal gyrus, supramarginal gyrus, and angular gyrus (Wernicke's area and adjacent tissue). Furthermore, poorer readers showed smaller correlations between the patterns of activation that did occur in the visual word form area and those in superior temporal and temporoparietal cortex. This evidence of reduced functional connectivity suggests specifically that communication between regions of the type that appears to be required for an effective vision–language interface was not being established.

Instead, poorer readers showed relatively greater activation in prefrontal cortex, especially inferior frontal gyrus in and around Broca's area as well as the right-hemisphere homologues of these areas. As Shaywitz and colleagues speculated, this increased activity in frontal speech-production-oriented regions may be in compensation for the poor connections from the visual system to posterior phonological regions—perhaps an attempt on the brain's part to substitute direct articulatory coding of printed words for the linguistically analytic aspects of phonological recoding that are the speciality of posterior temporal and temporoparietal structures.

As I demonstrate in the final section of the chapter, normal adult readers also show evidence that suggests direct articulatory coding in frontal motor regions, but they do so preferentially for high-frequency words that are likely to be familiar. Less familiar low-frequency words show evidence of greater reliance on posterior analysis in selecting an appropriate pronunciation, and all words produce activation in the temporoparietal regions that the above studies found to be silent in dyslexic individuals.

TEMPOROPARIETAL PHONOLOGICAL PROCESSING IN NORMAL ADULT READERS: COORDINATING LINGUISTIC ANALYSIS AND MEMORY RETRIEVAL. If the brain is relying on two kinds of knowledge about words—object-like word-specific retrieval from a lexical associative memory system and more abstract linguistic mappings from strings of graphemes to strings of phonemes—then a coordination problem arises. How are these two kinds of knowledge combined so that the right answer is obtained for any given word?

By definition, the two kinds of knowledge produce different answers for exception words, and hence compete. They produce the same answer for "regular" words consistent with the generalizable patterns and hence might help each other out. Behavioral studies of speeded pronunciation of single words produce evidence of exactly such cooperation and competition in the mature, well-established reading systems of young adults (for reviews, see Bernstein & Carr, 1996; Bernstein, DeShon, & Carr, 1998; Coltheart et al., 2001; Plaut, McClelland, Seidenberg, & Patterson, 1996). Pronunciation latencies are fast and errors are few for familiar, high-frequency words, and compliance with the generalizable patterns of spelling-to-pronunciation mapping makes only a small difference or no difference at all. Here, lexically specific associative knowledge, established and strengthened through many past encounters with each high frequency word, is sufficiently easy to access to override any conflict that might arise between the pronunciation suggested by the common patterns and the specific mapping required for that particular word. For low-frequency words, however, different results are observed. Lexically-specific associative knowledge is weaker for such words, because they have been processed many fewer times in the past, making consistency with the generalizable patterns a potentially stronger influence on the selection of a pronunciation. Low-frequency consistent words show evidence of cooperation between the two sources of knowledge—despite their lower familiarity, they are pronounced almost as rapidly and accurately as high-frequency words. Low-frequency exception words, in contrast, are pronounced 10% to 25% slower, and with higher error rates, than low-frequency regular-consistent words. Errors, though of course much less frequent than in surface dyslexia, follow the same tendency toward regularizations in which the exception word is pronounced as if it were a pseudoword. As word-specific associative knowledge about a particular word's pronunciation gets weaker and less accessible, the impact of the weight of evidence from generalizable patterns increases.

How to model the computations by which these two kinds of knowledge are taken into account and adjudicated is a contentious issue in cognitive psychology. There are divergent views concerning whether the two kinds of knowledge are represented together in a common format within a well-integrated and interactive "single mechanism"—the parallel-distributed-processing connectionist network approach (see Harm, McCandliss, & Seidenberg, 2003; Plaut, 1999; Plaut, McClelland, Seidenberg, & Patterson, 1996)—or in different formats with memory retrieval and application of generalizable patterns operating relatively independently of one another—the dual or multiple route approach (see Besner, 1999; Coltheart et al., 2001; Zorzi et al., 1998).

Behavioral data—reaction times and accuracies in word recognition experiments—have so far been unable to provide a definitive resolution. Perhaps one can gain a different kind of leverage on understanding this problem by trying to trace the functional anatomy that underlies the overall behavioral performances. Neuroimaging can be applied to this problem. To do so, however, requires diagnostic manipulations capable of identifying particular brain regions that might be involved in phonological recoding, and determining which if any of these regions are sensitive to the generalizable patterns alone and which rely on or interact with word-specific associative memory in carrying out their processing.

A straightforward approach to such diagnosis is to choose manipulations that make the sought-for processing harder or easier. An obvious choice for phonological recoding is regularity or consistency. Phonological recoding is easier for regular words that are consistent with the generalizable patterns. Phonological recoding is harder and more complicated for exception words—the sequences of graphemes contained in exception words activate a wider range of possibilities for how those graphemes should be pronounced. Whenever a decision must be made among a wider range of choices, that decision becomes more difficult. Hence regions of tissue that vary systematically in activation with a manipulation of consistency are candidates to be involved in phonological recoding.

How might one diagnose the involvement of word-specific associative memory? Whereas the generalizable patterns are just that—applicable to any orthographically well-structured letter string, even pseudowords that have never been encountered before, word-specific knowledge depends on having stored a representation in memory for a particular word, and being able to activate and retrieve that representation in an accurate and timely manner. Word-specific knowledge varies in strength as a function of the frequency with which it has been processed in the past, and stronger representations are easier to activate and retrieve. Hence word frequency is a candidate manipulation for diagnosing the involvement of word-specific associative memory. An interaction between consistency and frequency would suggest that a region of tissue involved in phonological recoding (as indicated by its sensitivity to consistency) relies on or interacts with word-specific associative memory in doing its job (as indicated by the fact that the consistency effect is modulated by the frequency of the particular word being recoded). Fiez, Balota, Raichle, and Petersen (1999) have used consistency and frequency in this way using PET.

A second possibility, and one that seems especially potent, is to use repetition priming as the diagnostic for word-specific retrieval. A recently activated word representation is more accessible regardless of frequency (Scarborough, Cortese, & Scarborough, 1977), and this increased accessibility can persist for minutes to hours—enough time to cover the duration of a neuroimaging experiment (Brown & Carr, 1993). Thus it can be determined whether a region identified as relevant to phonological recoding by virtue of its sensitivity to consistency is also sensitive to repetition priming by looking for an interaction between consistency and repetition in this region's activation. Such an influence of repetition priming would show that the recent activation of a specific word's memorial representation matters to the phonologically relevant processing responsibilities of this particular region.

Huang, Colombo, Carr, and Cao (2002, 2003) have applied such logic in an fMRI investigation that combined consistency of spelling-to-pronunciation mapping with repetition priming in a block design—four runs of trials, with each of these imaging runs consisting of periods of rest alternating with periods of reading words silently to oneself. Activation during the periods of reading was assessed against a baseline defined by activation during the rest periods immediately preceding and following each period of reading.

The repetition priming manipulation was implemented by having participants read a list of words outside the scanner at the beginning of the experiment, half with regular-consistent spelling-to-pronunciation mappings and half with exceptional mappings. These words appeared again in the scanner, the regular-consistent words during one of the four imaging runs and exception words during another. The other two imaging runs consisted of words that had not been seen before in the experiment, again with regular-consistent words in one run and exception words in another.

Huang and colleagues conducted two experiments following this design, one with high-frequency words and one with low-frequency words. In both experiments, two regions of inferior parietal cortex adjacent to Wernicke's area—supramarginal gyrus and angular gyrus—responded to consistency, with activation greater for exception words than for regular-consistent words, and showed no sensitivity at all to repetition priming. This activation tended to be bilateral. Treating the two regions as a single region of interest and testing for effects of hemisphere revealed equivalent left and right activation for high-frequency words, but a larger consistency effect in the left hemisphere than in the right for low-frequency words. In no case, however, was there an impact of repetition priming. Thus supramarginal and angular gyri taken together behaved as if they were involved in implementing the generalizable patterns of spelling-to-pronunciation mapping but without much regard for word-specific memory retrieval—their activity differed little as a function of frequency and not at all as a function of having just processed the same word a few minutes earlier.

While the supramarginal and angular gyri did not respond to repetition priming, sensitivity to recency of encounter with particular words was shown by other regions of tissue—in particular, Wernicke's area and its right-hemisphere homologue for low-frequency words, and frontal motor areas for high-frequency words. I now explore these effects. For low-frequency words, Wernicke's area and its right-hemisphere homologue produced a complex consistency by repetition interaction. For unprimed words, activation was greater for exception words than for regular-consistent words. But for primed words, this pattern reversed—activation was greater for regular-consistent words than for exception words, as if making the word's specific representation in lexical memory more accessible actually increased the difficulty of deciding between specific lexical information and generalized pattern-driven information, despite the fact that the two sources of information were pointing toward the same ultimate decision.

It is tempting to suggest from this complicated reaction to priming that Wernicke's area must be involved in managing and coordinating pattern-generated output from the supramarginal and angular gyri with word-specific and hence repetition-primable output from lexical memory. Before making such a suggestion, however, it is necessary to take into account the results for high-frequency words, which were different. For high-frequency words, Wernicke's area behaved similarly to the supramarginal and angular gyri, showing only an effect of consistency. But the consistency by repetition interaction was not lost—instead it moved. With high-frequency words, primary motor cortex and supplementary motor area were sensitive to repetition in this way, showing approximately the same pattern of activation that Wernicke's area showed for low-frequency words. Here, it is tempting to suggest that with the increased practice at turning written words into pronunciations, frontal motor areas can "go it alone," so to speak, in managing and coordinating the requisite knowledge and selecting an appropriate pronunciation, perhaps by direct reference to stored articulatory programs. Thus repetition priming as a diagnostic for reliance on lexically specific memory retrieval exposes a possible trade-off between anterior and posterior regions, in which the pronunciation of less familiar words is overseen by Wernicke's area, with its well-documented phonological sophistication, but pronunciation for more familiar words is taken up directly by the motor apparatus.

Conclusion

In this chapter I have described a preliminary study. Replication of these imaging results and further investigation of what kinds of codes are being generated or operated on by posterior versus anterior brain structures is needed before these suggestions about division of computational labor in the neural machinery of spelling-to-pronunciation translation can be regarded as more than speculation. Regardless of how the results obtained so far are ultimately interpreted, however, they do demonstrate that sensitivity to factors that influence selecting and producing a pronunciation are widely distributed through the brain. Consistency moderates neural activity in posterior and anterior regions in both hemispheres, and repetition priming moderates the sensitivity to consistency that is shown by some of these regions but not all of them. Much work remains to be done to map out the functional anatomy and processing characteristics of this network of regions—understanding the phonological and articulatory aspects of phonological recoding lags far behind the exquisite knowledge that has been gained of orthographic encoding in the visual word form area. This work will proceed using the tools of cognitive neuroscience that Posner has been so instrumental in helping to develop.

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