

## Dynamic Cortical Systems Subservicing Cognition: fMRI Studies With Typical and Atypical Individuals

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Functional brain imaging brings many new offerings to the table of cognitive neuroscience, particularly offerings that help refine our understanding of the dynamic and adaptive properties of brain function that underpin learning and development. It is a little ironic that a methodology that is classically associated with static, still images, should be informative about dynamics and plasticity. But the association is no longer correct. In the early days of functional neuroimaging, in the late 1980's, the scanners were less sensitive, so that all that was possible was a group average image depicting the areas of brain activation, averaged over several participants, contrasting a small number of experimental conditions. The current instrumentation, namely high-speed fMRI, is far more sensitive yielding enough data to observe reliable effects in single participants in a few minutes per experimental condition. Capturing the dynamics requires only a fast enough shutter speed and a willing subject.

One of the consequences of the new technology of particular relevance here is that it is possible to examine the cognitive system as it adapts to slight differences in the quantitative and qualitative demands of a particular experimental condition. The result is that the brain adaptation is clearly manifest, and this manifestation is one of the key offerings of fMRI: the hardware-software distinction in the analysis of cognition that was previously a useful heuristic scientific strategy obscures one of the main adaptive properties of mind. The hardware (brain tissue) is dynamically recruited to meet the processing needs. The underlying software and the neuralware in which it is implemented is constantly changing. It is likely that this dynamic recruitment scheme underlies performance not only in a changing cognitive task, but also underlies adaptation over a longer time frame in a changing world.

In this chapter, we explore several implications of a new perspective on cognition and its adaptiveness offered by cognitive brain imaging, focusing on examples in the of area of language comprehension. This chapter does not present the details of the theory, which appears elsewhere (Just, Carpenter & Varma, 1999). Here we summarize some of the main points of this theoretical perspective, and below we examine how they apply to issues of brain plasticity and atypical development. Some of the key hypotheses that are emerging from this perspective include the following:

- Cognition entails physiological work and resource consumption.
- A system involves collaboration among multiple neural components, a team.
- The team members may have multiple and overlapping functions
- The components are dynamically recruited
- As a behavior becomes more skilled, there is better coordination of its components
- Disturbance, such as cortical injury, can result in re-balancing the work load among the components
- Developmental syndromes, such as autism, may result in an unusual collaboration, with differential amounts of coordination within vs. among system components

We will first describe evidence for these hypotheses based on fMRI studies of normal young adults in high-level cognitive tasks. Second, we will describe some initial fMRI research with adults who have experienced stroke. Last, we will briefly describe some preliminary fMRI studies of individuals who are high-functioning intellectually, but also have autism.

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### I. THE CORTICAL SYSTEMS SUPPORTING COGNITION

**Cognition, resource consumption and mental work.** Cognitive computations entail physiological work. Moreover, the mapping between brain activation and a theoretical account of the underlying

processes depends not just on the type of processing that is occurring, but also on how much work is involved. This hypothesis contrasts the standard assumption that the mapping between brain activation and cognitive process depends only on the qualitative nature of the processes. This hypothesis is supported by neuroimaging studies that quantitatively vary the amount of task demand.

Before describing such a study, it is useful to briefly describe the methodology. Functional Magnetic Resonance Imaging (fMRI) exploits the fact that neuronal cortical activity is accompanied by local increases in the concentration of deoxygenated blood (Kwong et al., 1992; Ogawa et al., 1990). Using a powerful magnet (1.5 or 3.0 Tesla in our studies), fMRI detects the small increases (1-4%) in magnetic susceptibility of the hemoglobin in the microvasculature without any other contrast agent; hence, the method is called Blood Oxygen Level Dependent (BOLD). The typical study described here

compares the distribution of activation in a several experimental conditions to that of a rest condition.

**A sentence-comprehension study.** In the first fMRI study to manipulate the quantitative demands imposed by a sentence comprehension task, we contrasted the brain activation in language-related cortical areas for three kinds of sentences, shown in Table 1 (Just, Carpenter, Keller, Eddy & Thulborn, 1996). The three sentence types are superficially similar (each containing two clauses and the same number of content words), but they differ in structural complexity, and consequently in the demand they impose during comprehension, as shown in several behavioral studies (e.g. King & Just, 1991).

**Table 1: Three sentence types that differ in structural complexity (from Just et al., 1996)**

1. ACTIVE CONJOINED
2. SUBJECT-RELATIVE CLAUSE
3. OBJECT-RELATIVE CLAUSE

*The reporter attacked the senator and admitted the error.*

*The reporter that attacked the senator admitted the error.*

*The reporter that the senator attacked admitted the error.*

The fMRI-measured activation showed systematic increases with sentence complexity in a large scale network of cortical areas: the left posterior superior and middle temporal gyri (roughly, Wernicke’s area), the left inferior frontal gyrus (roughly, Broca’s area), and to a lesser extent, their right hemisphere homologues. Figure 1 shows an example of the data by illustrating the voxels in one slice that were significantly activated above the resting baseline (through the posterior temporal region) for the main conditions for one individual. Figure 2 shows the quantitative results when the voxels are summed for an entire cortical region and averaged across participants. In this particular study, the volume of activated brain tissue in left temporal

cortex increased from about .75 cm<sup>3</sup> in the processing of the least demanding sentence to about 1.2 cm<sup>3</sup> in the processing of the most demanding sentence. The right hemisphere homologue of this area is barely activated for the least demanding sentences, but is substantially activated for the most demanding ones. Such results demonstrate a dynamic recruitment of additional neural tissue within a region and across regions depending on the amount of computational demand that is imposed by the task. Thus, one cannot specify a particular region of the brain and declare “this is where sentence processing occurs.” Sentence comprehension occurs in a dynamically configured network of brain areas whose membership and degree of member participation depends on the comprehension task.

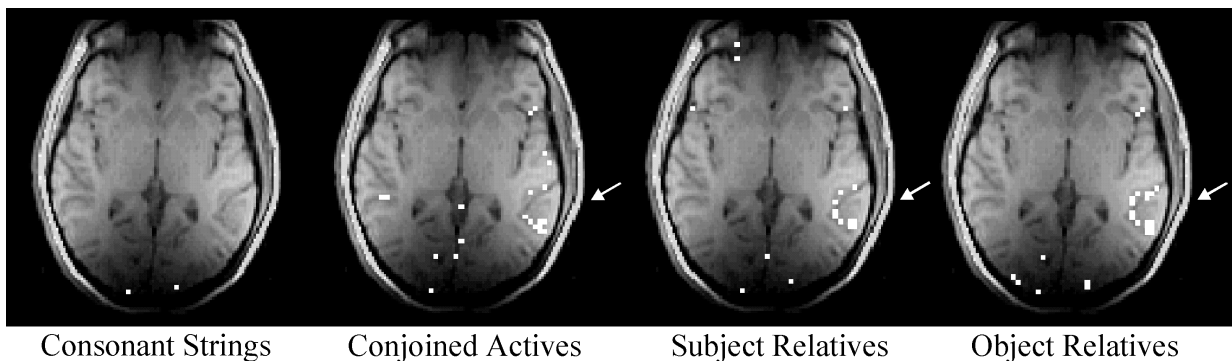


Figure 1. Thresholded fMRI activation images (1.5T) (superimposed on structural images) for only the most activated slice through Wernicke’s area (indicated by the arrow) from one participant. The number of activated voxels (shown in white) generally increases with sentence complexity. (From “Brain activation modulated by sentence comprehension” by Just, Carpenter, Keller, Eddy, & Thulborn, 1996, *Science*, 274, Figure 2, p. 115. Copyright 1996 by the American Association for the Advancement of Science. Reprinted with permission).

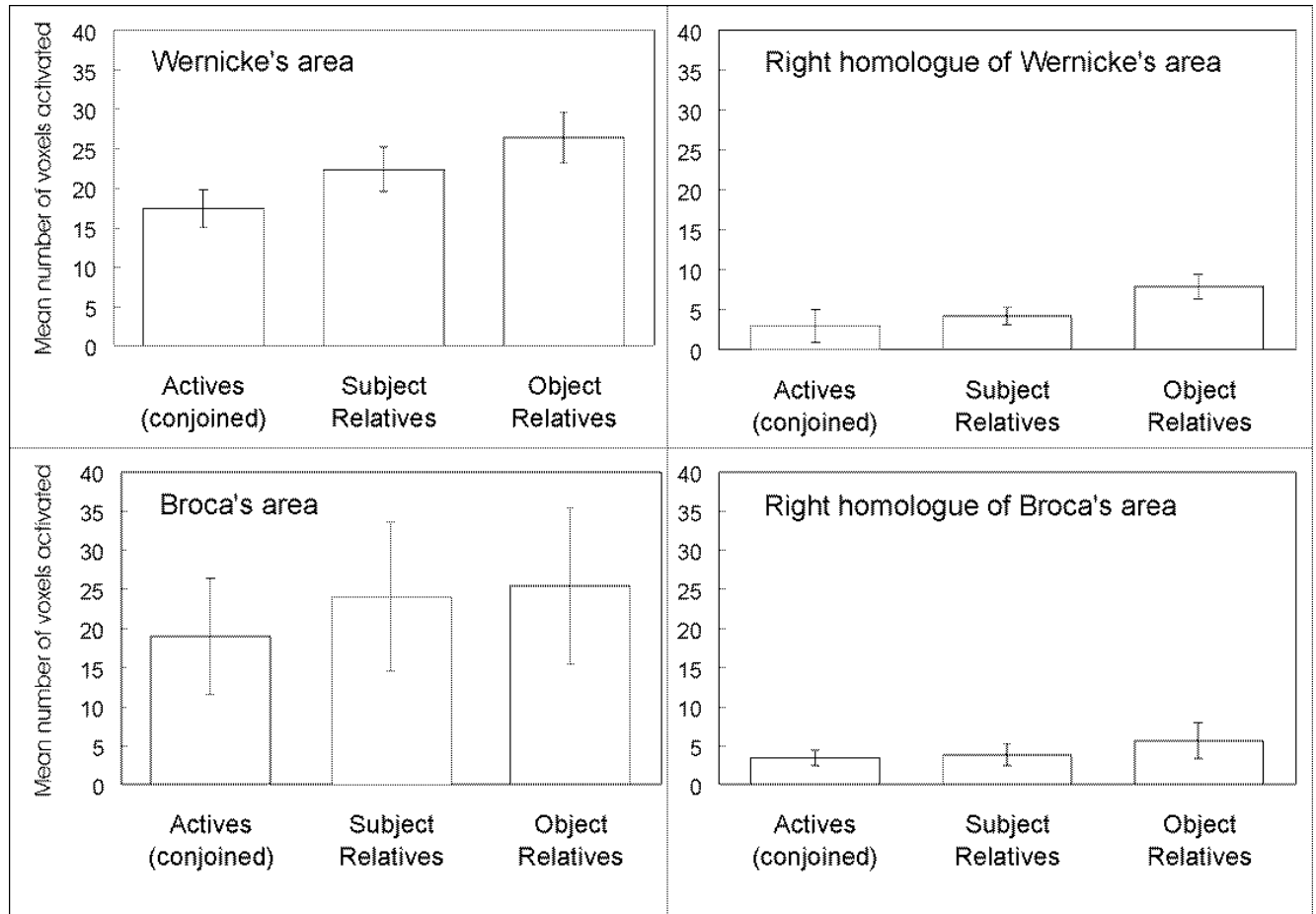


Figure 2. The average number of activated voxels across participants indicates that the processing of more complex sentences leads to an increase in the volume of neural tissue that is highly activated in all four areas. The top panels indicate the average number of activated voxels in the left (Wernicke's area) and right laterosuperior temporal cortex (and standard errors of the means over 15 participants). The bottom panels indicate the average number of activated voxels in the left (Broca's area) and right inferior frontal cortex (and standard errors of the means over only five participants). (From "Brain activation modulated by sentence comprehension" by Just, Carpenter, Keller, Eddy, & Thulborn, 1996, *Science*, 274, Figure 1, p. 115. Copyright 1996 by the American Association for the Advancement of Science. Reprinted with permission).

The same type of result has been found in some other domains, such as mental rotation (Carpenter et al., 1999) and short-term list learning (Grasby et al., 1994; Braver et al., 1997). In the research on mental rotation, we found that fMRI-measured activation in the parietal region increased monotonically with the amount of mental rotation required to align two three-dimensional Shepard and Metzler figures. Figure 2 shows how the fMRI-measured activation increases monotonically for both the left and right parietal regions; this activation is particularly in and around the intraparietal sulcus.

Both the sentence comprehension and the mental rotation studies assume that the mental workload is

being modulated by the independent variable. This assumption is based on several types of evidence. First, behavioral measures indicate that performance indices, such as response times and error rates, increase with the manipulation. Second, computational modeling studies that take account of resource utilization show in precise detail the extra computational work involved in comprehending more complex sentences (Haarmann, Just, & Carpenter, 1997; Just & Carpenter, 1992) or in mentally rotating through a larger rotation angle (Just & Carpenter, 1985). The fMRI studies show how the workload is distributed through the neural infrastructure of the cognition.

**Workload and time.** The workload of a system during the execution of some task can be distinguished from its sheer duration. Response time measures of task performance cannot make the distinction, because tasks can take a relatively long time but consume few resources. For example, in almost any resource-sensitive computational model, mentally adding a long list of single digit numbers ( $3 + 2 + 5 + 2 + 3 + 1 + 4 + 6 + 1 + \dots = ?$ ) consumes less activation than solving a complex mental multiplication task (e.g.  $63 \times 28 = ?$ ), although the list length can be manipulated to equate the processing time.

The fMRI experimental paradigms and the data analysis equate the duration of the data acquisition for the less demanding and more demanding trials, so these results indicate that the person is working

harder, not simply longer. In addition, in the mental rotation study, we contrasted the effects of cognitive workload and simply taking more time, by including a condition in which the participant had to scan a fixed grid, making more eye fixations and taking longer than the rotation task. The fMRI-measured activation in the parietal region for that condition, shown in Figure 2 as the “grid” condition, supports the distinction between computations that constitute additional mental work and computations that simply take longer, a distinction not possible with conventional behavioral measures. More generally, these types of studies suggest that the increased activation of nearby cortical tissue is a fairly general mechanism of adaptation to task difficulty. It is also consistent with the hypothesis that during a cognitive task, brain activation reflects cognitive work.

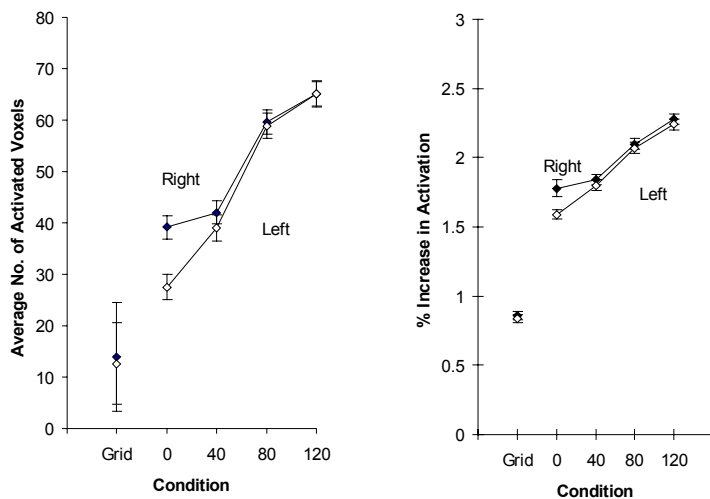


Figure 3. The average number of activated voxels for the left and right parietal regions increase as a function of the increase in angular disparity (left panel) and so does the mean percentage of increase in MR signal intensity over the fixation condition (right panel) for the 3.0T study. By contrast, the grid condition results in relatively few voxels that are significantly activated and a significantly lower increase in mean activation level. The results for the right hemisphere are shown by filled symbols and for the left, by open symbols. (From “Graded functional activation in the visuo-spatial system with the amount of task demand” by Carpenter, Just, Keller, Eddy, & Thulborn, 1999, *Journal of Cognitive Neuroscience*, Figure 5, p. 15. Copyright 1999 by the MIT Press. Reprinted with permission).

**Resource utilization.** Because all physical energy systems require resources, the concept of resource consumption is not novel from the perspective of biology. In fact, many neuroimaging techniques depend on one or another aspect of biological resource consumption. Glucose metabolism underlies PET- FDG; and as explained above, the BOLD fMRI technique assesses the concentration of oxygen the hemoglobin that flows to a region with a high degree of neural activity. In contrast to biological models, the concept of resources is not well represented in many cognitive science models, particularly computational theories which instead focus on abstract descriptions of cognitive computations and representations.

However, the concept of resource consumption in a computational model can bridge from the abstract domain of functional description into the concrete domain of neural implementation.

An index of the amount of work that a cognitive system performs can be used to map between the computational level and physiological measures of thought (such as brain activation). One such index (adapted from economics) is called *resource\_utilization*, an index of the rate at which an activity (such as processing information) consumes resources. But how should resources be construed in a computational model? In a simulation model of sentence comprehension, resource utilization corresponds to the rate at which different subsystems utilize functional activation (Just & Carpenter,

1992, 1993). The term “activation” has a long history of usage in cognitive science, and typically denotes the availability of a concept in memory. In the comprehension model, each element has an associated activation level that indicates its availability in working memory. In addition, functional activation also plays a role in computation because computations occur through the gradual increase in the activation levels of intermediate and final products, as occurs in connectionist models (McClelland & Rumelhart, 1986). For example, more functional activation is used in the course of constructing and maintaining the representations of the more complex sentences with object-relative clauses than for the less complex sentences. Within some dynamic range, the amount of functional activation that is needed to accomplish a task is expected to correlate with the fMRI-measures of brain activation.

**Networks and brain regions.** In contrast to a localist assumption of a one-to-one mapping between cortical regions and cognitive operations, an alternative view is that cognitive task performance is subserved by large-scale cortical networks that consist of spatially separate computational components, each with its own set of relative specializations, that collaborate extensively to accomplish cognitive functions. For example, visual sentence comprehension is subserved by a large-scale network that includes left inferior frontal gyrus (Broca’s area), left posterior superior temporal gyrus (Wernicke’s area), angular gyrus, extrastriate and primary visual cortex, and in some circumstances, left middle frontal gyrus (left DLPFC) and the right hemisphere homologues of Broca’s and Wernicke’s areas. For example, Figure 4 shows the thresholded statistical probability maps for fourteen slices (each 5 mm thick) that were obtained during a sentence comprehension task and are superimposed on structural images taken of the participant. Note the large number of regions, only some of which are labeled, that show activation. Thus, no single area “does” sentence comprehension. Furthermore, the collaboration among areas is hypothesized to be highly interactive (to be discussed below), making the resulting cognitive computations an emergent property of several collaborating team members. This analysis applies not just to visual sentence comprehension, but to any cognitive task of any complexity whatsoever.

Moreover, neuropsychological research on patients with brain damage has produced a

compatible view. Even localized lesions produce non-modular deficits, affecting performance in a variety of tasks (Mesulam, 1990). Further supporting this view is the concept of distributed processing that has been fostered by connectionist models (McClelland & Rumelhart, 1986; Elman et al., 1996). Mesulam’s proposal of distributed processing in a large-scale network consisting of multiple brain areas applies the connectionist distribution principle several levels higher.

A second emerging hypothesis is that neural components may participate in supporting more than one function, although a region may preferentially perform a certain type of operation, reflecting a *relative specialization* rather than an absolute and exclusive involvement. In neuroimaging studies, a particular cortical region may be activated in a family of tasks.

The differential effect of various types of computational demand on each member of a large scale cortical network can be informative about the organization of the network. In the domain of sentence processing, we have found that effects of sentence complexity are far more pervasive than expected, and they interact with other types of computational demand. For example, we have recently examined the effects of sentence complexity in conjunction with the effects of lexical frequency (using the same type of paradigm as above) with a 3.0T scanner on 14 5mm slices covering most of the cortex (Keller, Carpenter & Just, 1999). As reported above, the sentence’s structural complexity affected the amount of activation in both the left posterior superior/middle temporal region (Wernicke’s area) and the left inferior frontal region (Broca’s area). In addition, sentence complexity affected the activation in other regions as well, including the left and right ventral striatal pathway, regions that are more associated with visual form processing, as well as the precentral sulcus, the intraparietal sulcus, and DLPFC (dorsolateral prefrontal cortex). Equally importantly, the effect of the sentence’s structure typically interacted with the normative frequency of the nouns in the sentence, and this interaction, always taking a similar form, occurred in several areas (Broca’s and Wernicke’s prominent among them). In general, the sentence’s structure had a much a greater effect on brain activation if the nouns in the sentence were infrequent than if they were frequent (an overadditive interaction between the two types of demand). This existence of an interaction within a given brain region indicates that more than one type of process (in this case, syntactic and lexical) involves the region. The occurrence of the interaction in multiple brain regions indicates the collaboration among areas, such that the creation of a greater workload of one area is propagated (as more work)

for another area. The results speak to the multi-specialization of areas and the collaboration among areas.

Any conclusion about the mapping of a particular region is limited by the spatial resolution of the methodology. For example, the spatial resolution of fMRI is excellent and rapidly improving; nevertheless, it is always possible that within whatever spatial resolution is present, there is some finer subdivision that cannot be detected. However, our viewpoint postulates that cognitive representations and processes are not coded by

individual components (be they neurons or small cortical regions), but rather that they are coded by the relations among neural components, which can undoubtedly be characterized at multiple levels. Even methodologies that record from single cells but examine a large number of them are reaching similar conclusions about the dynamic, interdependent nature of the underlying activity (Nicoletis, 1997; Sanes & Donoghue, 1997a, 1997b; Sanes et al., 1995). The localization of function is an old problem in psychology, with fMRI providing a somewhat new type of answer: limited regional equipotentiality with extensive inter-regional collaboration.

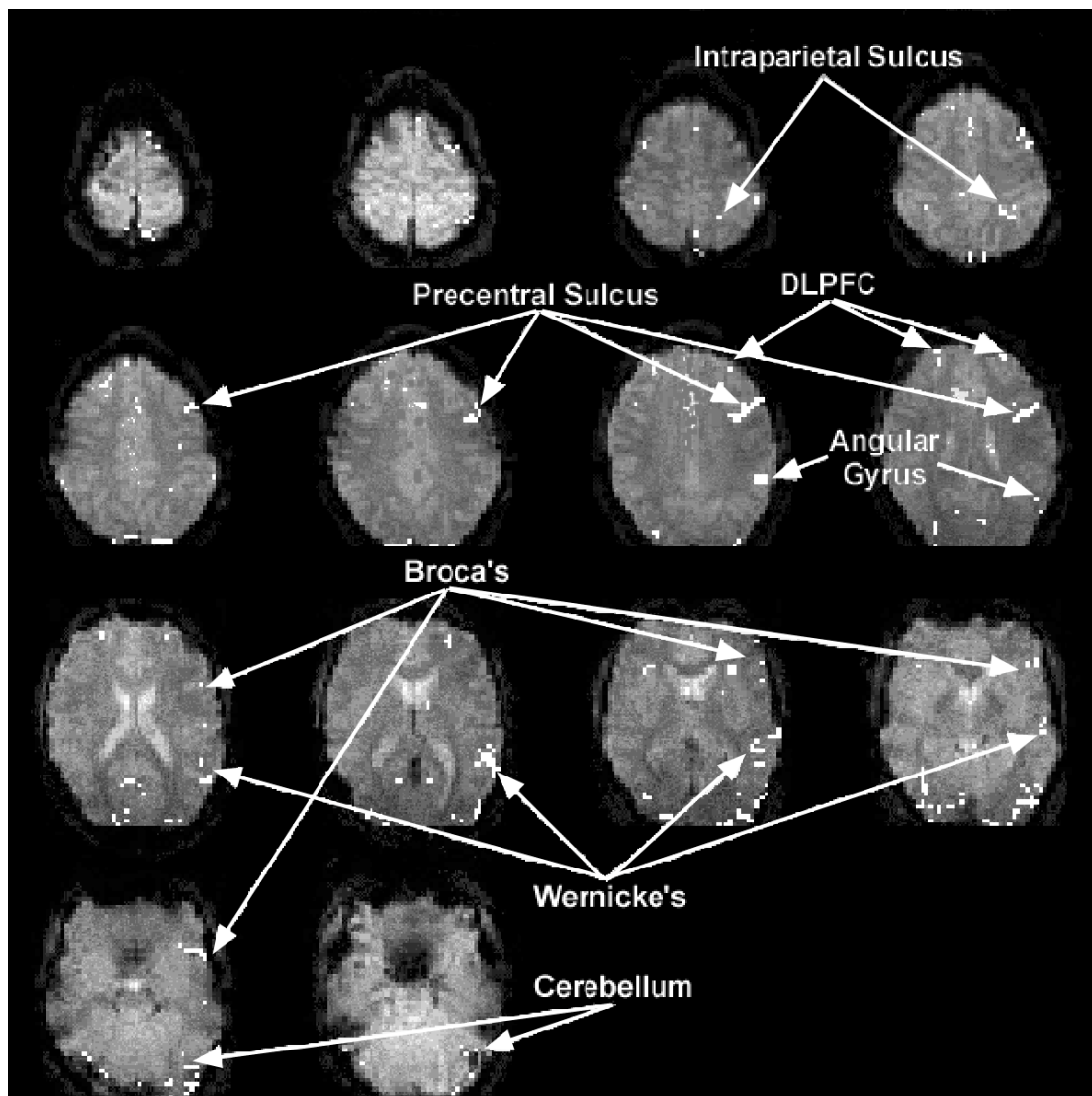


Figure 4. Statistical probability maps superimposed on structural images for a single individual to illustrate how a cognitive task (like sentence comprehension) elicits activation in multiple cortical loci. The voxels in white are those that are significantly activated above a baseline fixation condition when a normal college student reads a series of sentences. The 14 axial-oblique slices were acquired with gradient echo, resonant echo planar MRI at 3.0T. (From "Modeling the mind: Very High-field fMRI-activation during cognition" by Carpenter, & Just, 1999, *Topics in magnetic resonance imaging*, 10, Figure 2, p. 18. Copyright 1999 by Lippincott, Williams, & Wilkins. Reprinted with permission).

**Dynamic recruitment and lateralization.** The lateralization of activation in the temporal region for sentence comprehension tasks provides one perspective on the flexibility of network configuration. Across a number of reading studies with normal, right-handed college students, we found much more activation in the left posterior superior and middle temporal region than in the right. The degree of lateralization can be quantified by measuring the difference in the activation in the two homologues (Left - Right) relative to the total activation across the hemispheres (Left + Right), an index that ranges from +1 for an entirely left-lateralized pattern, to -1 for an entirely right-lateralized pattern. In a study involving 30 right-handed college students with the sentence comprehension paradigm that was described earlier, the mean of the index was 0.80 (S.D. = .3) for the posterior superior and middle temporal region, with the most right lateralized value being -0.2 for these right-handed individuals. This indicates that the activation was very left lateralized for this region and task (Keller, Carpenter & Just, 1999).

The activation in this region is more bilateral when participants read sentences that have a concrete, visuo-spatial referent that they expect to see (Carpenter et al., 1999). The amount of activation in the right posterior temporal region almost equaled that in the left as participants read sentences like *It isn't true that the star is above the plus* before examining a subsequent picture (such as a plus above a star). The fact that the left and right posterior temporal regions were almost equally activated in this instance illustrates how the language networks are dynamically configured. The degree of involvement of the right temporal area reflects in part the content of the task.

Listening comprehension also may be more bilaterally represented in the temporal region than reading comprehension. This conclusion is supported by two studies that contrasted the two modalities. One involved verifying general knowledge questions (such as *The study of economics concerns the distribution of wealth and goods*). For the ten college students who performed the task visually, the laterality index for the superior/middle temporal region was 0.65; by contrast, for the ten who performed the task auditorily, it was 0.17. (In the latter case, we separately coded and excluded the primary auditory cortex, which is expected to be bilaterally activated.) A second study contrasted reading and listening to active and object-relative

sentences followed by questions as in the earlier Just et al study (Michaels et al., 1999). That study showed a similar shift in the laterality index, with a value of .63 for reading and .07 for listening. These analyses suggests that there are secondary and higher-level association regions in the right temporal region that are activated by the auditory comprehension task. The apparently greater lateralization in the temporal region for reading than for listening comprehension (for normal, right-handed adults) is itself an interesting phenomenon. These studies suggest that there isn't a single language comprehension system, even in the posterior temporal region. The differential lateralization suggests that language comprehension is accomplished by somewhat flexibly configured subsystems that may partially overlap but also may partially diverge, depending on the precise properties of the computational demand. Such data are consistent with the more general argument that the systems underlying cognitive performance are dynamically configured and allocated as a function of both the quantitative and qualitative properties of the task as well as the availability and history of the neural systems themselves.

Another mechanism of dynamic allocation is the recruitment of additional neural components into the network underlying task performance. To take an example from language processing, the participation of a goal-monitoring/executive system (often associated with the prefrontal cortex) may depend on whether the sentence comprehension requires a substantial amount of reasoning. If a typical college student is given even a complex sentence to understand, this processing usually activates a set of cortical regions that does *not* include DLPFC. By contrast, the executive system should be much more likely to enter into the network if the task involves complex reasoning, such as in understanding *Brothers and sisters have I none, but this man's father is my father's son*. (The problem is to determine the family relation between the speaker of this sentence and the person depicted in the portrait to which the speaker is referring, (Casey, 1993). Although system components may enter or exit a network, equally often the components simply participate to a greater or lesser degree. For example, normal college students who are trained in a sentence comprehension task show relatively little activation (less than 1 voxel, on average) of DLPFC; if the same task is embedded in a dual task situation, the amount of DLPFC activation doubles.

**System combinatorics.** A systems approach to cognition raises the issue of what constitutes a cognitive system. Several recent taxonomies can be defined by task domain. For example, Gardner's (1983), theory of multiple intelligences, which grew out of his consideration

of both neuropsychological and developmental data, suggested seven systems -- linguistic, spatial, quantitative, music, kinesthetic, interpersonal, and intrapersonal intelligences. Moreover, a meta-analysis of a very large compendium of psychometric data suggested an overlapping set of candidate systems: general reasoning, verbal language comprehension, rote memory, visualization, auditory perception (including music), creativity and speed on low-level tasks (Carroll, 1993, p. 626). A third proposal, based on the deficits of patients with focal lesions, distinguished spatial attention, rote memory, and language systems, without an attempt to be exhaustive (Mesulam, 1990). These taxonomies usefully capture some empirical observations concerning the partially dissociable effect of lesions in adults and the patterns of individual differences.

While useful, such taxonomies lack the generative and combinatoric properties that are needed to capture the spectrum of cognitive skills that humans acquire, including skills that didn't exist during the development of Nature's original toolkit for human intelligence. The notion of combinatorics is central if we are to account for the human ability to learn and adapt to such a wide spectrum of environments, from programming in Java, or flying a lunar module, to proving a theorem in topology. The combinatoric approach proposes that larger systems reflect the recruitment of smaller subsystems, perhaps with different weights and orders. However, the recruitment is not simply some linear concatenation because the components themselves are affected by the other components with which they collaborate.

**Developmental implications.** Although we have discussed recruitment over in the context of short time spans, dynamic recruitment may be the appropriate characterization for discussing learning and development as well. During development, the cortical systems are recruited as described above, but the relative specializations and degree of collaboration are probably much less well established. The developmental account must explain how the end state we describe can arise from some initial state. Elman and his colleagues (1996) suggest that the cortex in the neonate starts with differentiated regions containing cells that are differentially proficient in various types of processing. Repeated exposure to different types of processing can result in some areas gradually becoming more proficient (and hence specialized) in particular types of processing, namely those types of processing for which the given cell types are most

suited. The fMRI contribution here is that the cycles of learning in this account require a dynamic recruitment of multiple possible areas in performing a task. As a task is repeatedly performed during development, there is a differential increase in proficiency of the best suited area for a given computation. Moreover, this learning regimen can also lead to some redundancy of function across areas, such that inherently less proficient areas could also accrue some degree of proficiency. For example, cells in more than one brain area may initially attempt to process speech sounds, but the area containing cells that are particularly sensitive to the fine timing distinctions that differentiate phonemes may eventually become specialized for speech processing. Another area may also have initially attempted to process speech, and eventually lost the competition for the specialization, but may nevertheless have retained a residual capability to process speech, albeit less efficiently. Thus there might be some overlap in function between areas, such as between the left and right homologues of the language network.

There is much more to cognitive development than recruitment of brain areas, but the flexibility of the brain response to task variation in adults provides a possible clue to the development of large scale cortical networks. In a developing child, any new task might evoke a network of brain areas which might initially constitute a larger or different set than in an adult, by virtue of the task properties evoking even remotely relevant areas. With practice and learning, the best suited areas come to be favored, and probably increasingly collaborate with each other. This same account applies equally to learning in adults, where the increased collaboration between areas with learning (measured as increased synchrony in fMRI activation) has been demonstrated (Buchel et al., 1999).

## II. RECRUITMENT AND PLASTICITY: EVIDENCE FROM INDIVIDUALS WHO HAVE HAD A STROKE

The dynamic recruitment and overlap of function across areas underlies not only development, but also adaptation to brain damage. One clue can be found in a recent set of fMRI studies of adults who have had left hemisphere strokes that affected their language comprehension ability. The first study examined two individuals soon after their strokes, and the results suggest that there can be relatively rapid recruitment of the right-hemisphere homologues of the classic language cortical regions. Two adults were studied using a sentence comprehension paradigm shortly after the acute phase of their strokes and a few months thereafter, while they showed spontaneous language recovery (Thulborn,



Carpenter & Just, 1999). One individual had been studied prior to his stroke, and so constitutes a rare before-after case study. Of the two patients, one had a left anterior stroke (B) and the other, a stroke in the left posterior region (W). For both patients, the fMRI data obtained shortly after the stroke showed that there was more right hemisphere activation in the area that was homologous to the stroke than the normal controls. Moreover, the relative amount of activation in the right homologue increased over time, suggesting a redistribution of the workload in the language network. For both individuals, this redistribution was accompanied by a relatively rapid improvement in language skill, eventually resolving in mild language deficits. The redistribution is consistent with other PET neuroimaging studies that were performed years after the patients' strokes and indicated considerable right hemisphere involvement (Weiller et al., 1995; Engelien et al., 1995).

**An fMRI-study of young children.** The redistribution of language processing to the homologous hemisphere was also found in a fMRI study of school age children who had early left-hemisphere focal lesions (Booth et al., submitted). These children participated in a fMRI written sentence-comprehension study that was essentially identical to the Just et al. (1996) study with college students. The children with left-hemisphere damage showed activation in the typical language processing areas, but the activation was strongly right lateralized. These data suggest that when a lesion has damaged the preferred mechanisms, then the participation of the right homologue is increasingly recruited. Such an interpretation is also consistent with the behavioral data from a similar population of children who showed delayed language production, but more normal language skills by the school age years (Stiles & Thal, 1993). The general plasticity pattern here is to recruit areas to a task that were secondary in proficiency, but nevertheless had the potential for the task or had actually participated in the task performance previously. In effect, this mechanism recruits an existing member of a large scale network to perform the function of a damaged component, a function that the intact member may have previously performed in a secondary (less proficient) role.

**An fMRI study showing prefrontal recruitment with language therapy.** Another mechanism of plasticity in response to brain damage may implicate the recruitment of the prefrontal regions in conjunction with the learning of a new

strategy. The learning study involved two adults with aphasia, long past their focal left-hemisphere stroke who underwent an intensive language therapy program (Just et al., 1999). Both individuals had difficulty understanding sentences at the beginning of the therapy, but by the end, showed significant behavioral improvement and generalization to other sentences. The therapy was a version of semantic mapping therapy (Schwartz et al., 1994); it involved the auditory presentation of a variety of sentences and the participant had to identify the semantic roles of the individuals mentioned in the sentence.

Both before and after the therapy, the patients participated in a fMRI study that contrasted the visual comprehension of structurally simpler and more complex sentences. Before the therapy, the patients could not understand any of the more complex sentences (i.e. they could not answer simple comprehension questions about sentences that they had just read), and correspondingly, they had little activation in the language regions (Broca's and Wernicke's areas) for those conditions. However, when simpler sentences were presented, these patients were able to understand them and their brain activation looked approximately normal. After the therapy, however, the patients were able to understand complex sentences with reasonable accuracy. At that point, there was activation in the language regions for all three types of sentences presented, with increasing amounts related to the increasing complexity of the sentence. In addition, however, post-therapy there was pronounced activation in the dorsolateral prefrontal region, a region that typically shows relatively little activation for college students in this paradigm. For the patient with an intact left DLPFC, the new activation, which increased with sentence complexity, occurred in left DLPFC. For the patient in whom left DLPFC had been damaged, the new activation occurred in right DLPFC.

The suggestion of these results is that a new member was recruited into the network; the recruited region is associated with planning, problem solving and sequential analyses. Our interpretation of these results is that the behavioral therapy regimen instilled a new set of strategic processes for sentence comprehension, and this new component of processing was supported in least in part by the involvement of the prefrontal regions. Of equal interest is the fact that the new DLPFC involvement was associated with re-newed involvement of the language regions during the processing of complex sentences. The DLPFC role was collaborative, entailing activation of other members of the network which had previously been absent.

This result cumulates with developmental studies that have used EEG (e.g., Case, 1992; Thatcher, 1992) or have

analyzed the effects on children who have had early lesions in this region. Those studies indicated that there may be prefrontal involvement throughout development, but there is some suggestion that this area is particularly important during adolescence and the child's increasing ability to do more abstract thinking. Such data suggest that the prefrontal regions may be particularly implicated in learning and development, although not exclusively. Rather, the role of the prefrontal region may be dynamic; it may be particularly useful in assembling and coordinating subsystems in the early stages of learning, and its role may actually decrease with learning and automaticity.

### III. SPECULATIONS ON THE DEVELOPMENT OF COGNITIVE SYSTEMS

**Mechanisms of dynamic recruitment.** The recruitment of cortical systems is dynamic through the course of a child's development, as it is the adult, although the recruitment latitude is much greater in the child. The qualitative processing characteristics of the various cognitive systems that emerge surely reflect both the child's biological propensities as well as his or her socio-cultural experiences. Piaget postulated that the sensory-motor reflexes of the very young infant constitute the scaffolds of cognition. A specific instantiation of this shaping process can be observed in the development of visual attention (Johnson, 1997). Johnson has studied the orienting of young infants toward head-like visual patterns, and he also has studied how young birds imprint on patterns that resemble mother hens. Based on both behavioral, animal and physiological studies, he argued that early processing systems shape the infant (or baby bird) to attend to certain features of the environment (i.e. head-like patterns). This selection mechanism then biases what is available to the other organizing systems of the developing infant. Hence, the cortical systems that are phylogenetically shaped for certain broad types of information (say visual lines, patterns, and motion in conjunction with human sounds), then receive correlated information that corresponds to an event like "Mother picking up, cuddling and talking to the baby." Thus the early sensory-motor reflexes biases the developing cortical and subcortical systems by filtering what otherwise could be a "booming buzzing confusion."

Dynamic recruitment during development is also consistent with the studies of individuals who are either congenitally blind or congenitally deaf

(Neville, 1993). Those studies suggest, for example, that there is auditory processing in the occipital region of congenitally blind individuals, suggesting both plasticity and dynamic recruitment of that region. This view is also consistent with the general point of *Rethinking Innateness* (Elman et al., 1996), which argues that the existence of highly organized cortical systems in the adult does not imply that such systems are pre-wired in the infant.

Another component of this view is that the neural systems that support cognition are not internally closed systems, but rather they are shaped by the activities of the person in the world. The idea that the person and environment form a system is one way to incorporate the constructivist views espoused by numerous developmentalists. It is also consistent with the concept of affordances, from Gibson's perceptual theory (Gibson, 1979), which stresses that the environment is coded in terms of what it affords perceptually and motorically. All of these perspectives point to the inherent role of adaptation in development and learning, adaptation that is shaped both by the environment as well as the individual.

#### *The qualitative properties of developmental systems.*

Piaget suggested that the sensory-motor schemas are the foundations for the next systems to develop, which he proposed, are the schemas of the permanent object, space, time and causality (Piaget & Inhelder, 1969). Of course, these schemas are interdependent since the permanent object is the argument that undergoes the transformations through time and space, and is linked into events through causality. An extrapolation of the Piagetian approach is to propose that these systems, plus others, contribute to the genesis of other cognitive systems. To illustrate how this might occur, we can look at language development. The acquisition of sign language by congenitally deaf infants parallels the acquisition of spoken language by hearing infants in both the nature and sequence of the content and timing of particular developments. These parallels have led at least one researcher (Pettito, 1996) to suggest that the unifying dimension underlying signed and spoken language is temporal organization. (This is not to deny the role that space can play as a communicative tool as well as a topic, but simply that the invariant code may be temporal). Time may be one of the features, along with social communication, that gives rise to the elements that become organized. The emerging system may build on the initial sensitivity to temporal information (as well as other sensitivities), and the emerging language systems have their own unique properties.

**Coordination and collaboration in system development.** Complex systems, whether biological or social, involve the coordination of activity across components. In the case of cognitive skill, this

coordination occurs across a variety of cortical and subcortical components.

One mechanism of coordination may relate to the time course of activity across units. This hypothesis is a generalization of Hebb's (1949) proposal that co-activation at the neural level is a mechanism of learning, specifically, a mechanism for constructing the cell assembly. The current proposal extends this insight to suggest that coordinated activity (not necessarily just activation) among larger units might lead to the organization of still larger units, up through networks and large scale cortical networks systems.

A second aspect of this issue may be more appropriately labeled "collaboration;" it is the sharing of cognitive computations. Collaboration among components may be important in cognitive development because it may allow for greater specialization of individual components, analogous to the way in which collaborations among individuals in a work environment allows for individuals to develop deeper skills. It is important to keep in mind that specialization and collaboration (in the sense of frequent communication of relevant information) are mutually compatible. The other side of the coin is that collaboration may foster some variation in how computations are performed; such variation may provide the backup that can be drawn upon if the environment becomes more demanding or the individual changes. A component that works closely with another component may learn a secondary specialization, one that can be recruited when the primary component is occupied or otherwise unavailable. For example, the conjoint modulation of the inferior frontal and posterior superior temporal region in language processing is indicative of such collaborative processing. The particular primary computations of these regions appear to be so collaborative that the two areas are similarly affected by many, but not all language factors (Just, Carpenter & Varma, 1999).

These speculations about system collaboration may be particularly important in the case of neural development. Impediments to the normal development of any individual component, to their coordination or specific collaboration may affect a number of different types of cognitive tasks. And any such impediment is also likely to affect the development of other components that are without a primary problem, because the entire network must adapt to the unusual coordination or collaboration. This point was noted by Parks et al. (1988, p. 277) in

the context of a theory of network efficiency; he noted that dysfunctional neurochemical systems or developmental inadequacies in particular neural structures could result in poor feedback. This poor feedback could lead to the inadequate recruitment and poor organization of processing elements, resulting in the inefficient communication within topographically separated assemblies of neuronal networks.

#### **IV. IMPAIRED AND PRESERVED SYSTEMS IN AUTISTIC INDIVIDUALS**

Autism is the prototype of a developmental disorder that has a wide-ranging impact on both social and cognitive behaviors. Individuals with autism often show a lack of reciprocity in social give and take. As children, they may lack interest in playing with toys, and as adults, they typically have a restricted range of interests, although they may develop great focus and expertise in the domains that do draw their interest. Of particular relevance here is the fact that individuals with autism often show deficit language skills and difficulty with problem solving and self-initiated conceptual behavior, sometimes characterized as problems with the executive system (Hughes, Russell & Robbins, 1994; Hughes, 1996; Minshew, 1996; Minshew, Goldstein & Siegel, 1995; Ozonoff, Pennington & Rogers, 1991). Executive deficits have been documented for preschool children, older children, adolescents and adults with autism (Ozonoff et al 1991; Ozonoff et al 1994; Rumsey, 1985; Rumsey & Hamburger, 1988) and longitudinally (Ozonoff & McEvoy, 1994).

That autism is not some global retardation is indicated by the fact that these individuals have an uneven profile of abilities, with remarkable gifts as well as limitations. In a large sample of individuals with near normal or above normal IQs, the more pattern-oriented skills, such as word decoding and visuo-spatial processing, of the individuals with autism, exceeded the skill levels exhibited by age and IQ matched controls (Siegel et al., 1996). Even more dramatic are the prodigious talents of artists such as Nadia (Selfe, 1977), the incredibly complex buildings designed by Temple Grandin (Grandin, 1995; Grandin & Scariano, 1986), and skills of calendar calculators and musical prodigies (Howe, 1989). Again, these skills tend to involve patterns, either visual-spatial, musical or numeric, that can be the basis of complex achievements that are beyond the capability of "normal controls." The skills tend not to be in linguistic, abstract reasoning or social domains. The unevenness of the profile of individuals with autism is

important for theories of autism as well as theories of cognitive development in general.

Our fMRI research on autism is a preliminary progress report of a project to map between cognitive performance (based on behavioral studies) and cortical function (using fMRI) in the language and executive processing domains for individuals who are high-functioning (IQ's in the normal range) and who have autism. These individuals have all the criterial characteristics of autism, but its less severe form allows a more normal developmental environment. In addition, the characterization of cognition in high-functioning autistic patients that has been developed by one of us (Minshew, Goldstein & Siegel, 1995, 1997) seems particularly compatible with the systems approach that has emerged from the fMRI studies of young adults and patients. The general framework suggests that cognitive deficits in autistic individuals are due, in large part, to difficulties with higher-order abstraction (Ozonoff, 1995; Minshew, Goldstein & Siegel, 1995, 1997). This preliminary report should not be over interpreted because it is based on a small number of participants and an incomplete analysis of the data. Nevertheless, we have discovered some regularities, which are compatible with and make concrete the notion of a deficit in higher-order abstraction.

Psychometric test results suggest that the language deficits of individuals with autism appear primarily when the processing demand is high. In fact, in a battery of psycho-educational tests, the largest and most reliable difference between a sample of high functioning (IQ>70) individuals with autism and age and IQ-matched controls occurred with a test called the Detroit Test of Oral Directions (Goldstein, Minshew & Siegel, 1994). The Detroit Test is a type of language working memory test. It consists of a series of picture sets of several common objects (e.g., a pail, baseball, hat, and bird). With each set, the participant hears a set of directions, such as *draw a circle around the baseball, draw a line through the hat, circle the container and draw a line to the bird without touching the other items*. Because the participant isn't allowed to begin any action until all of the directions are heard, the individual must process and simultaneously store a sequence of commands. The complexity of the test increases through 3 main manipulations: (a) the successive sets increase in the number of items and number of instructions, (b) the phrase used to denote a picture can be more abstract rather than concrete (e.g. *container* vs. *pail*), (c) several cognitive operations

may be embedded in one direction (e.g., *cross out the triangle* vs. *cross out the biggest number that is in a square*). All three factors can be viewed as ways to increase the demand on the language working-memory system that must both process and store linguistic information; hence, the deficits were associated with a highly demanding working memory task. These findings are especially noteworthy precisely because the groups were matched for IQ. A likely explanation is that the difference in language processing between autistic and control individuals arises if the language task makes a substantial demand on executive processes to coordinate the memory and processing demands.

**Multiple deficits hypotheses.** One type of hypothesis concerning autism is that it is a syndrome of multiple primary deficits (e.g., Goodman, 1989, 1994), and two such proposals are particularly relevant to the current context. One proposal links the deficits in executive processing to the frontal system (Ozonoff, Pennington & Rogers, 1991). There is evidence of metabolic abnormality in the frontal system in the cell membranes that are vital to synaptic function. A hypermetabolic energy state (abnormally decreased levels of phosphocreatine) was found in the dorsal prefrontal cortex of 11 high-functioning autistic adolescent and young adults, using NMR spectroscopy (Minshew, Goldstein, Dombrowski, Panchalingam & Pettegrew, 1993). Also, the degree of metabolic abnormality correlated with performance in complex language and problem solving tasks. The fact that the correlation occurs with complex comprehension suggests that the dysfunction plays a role in more domains than those that are explicitly labeled "executive." Note that this frontal hypothesis does not exclude the possibility of other sites of dysfunction, including, for example, the rather widely documented abnormalities in the cerebellum (Courchesne, 1997). Indeed, such a possibility is consistent the data reported in this volume (Galaburda & Rosen, this volume) showing that cortical lesions in a developing animal can cause the malformations in a subcortical region. Such data suggest that neural development is interactive, and it is the degree and nature of that interdependence that needs to be elucidated.

A second and not mutually exclusive hypothesis arises from the interdependence of various components in a network. This second hypothesis is that autism affects the interconnectivity among and within various cortical systems. A relative lack of interconnectivity might explain why the difficulties of high-functioning individuals with autism span a variety of complex information-processing tasks. At present, our research gives no indication of whether such a problem might be

traced to a single or multiple neurobiological mechanisms. Rather, our goal is to produce a more precise description of the functional characteristics and neural correlates of the relatively preserved and compromised systems.

**An fMRI sentence comprehension study.** To examine these hypotheses in the area of language processing, we used a simplified version of the sentence-comprehension paradigm that was described above. Currently, the study involves approximately 11 individuals with autism (depending on the particular study) and half that number of control subjects who are matched in age, gender and IQ. The comparisons between the individuals with autism and the controls concerned several key issues:

- Do the same areas activate during the task?
- Do the different areas activate to the same relative degree?
- Is the activation between and within activated areas equally coordinated?

We presented affirmative active and passive sentences containing high frequency words, which we knew to be easily comprehensible for this group. The sentences were constructed so that either noun was equally likely to perform the action, for example, *The boy told the farmer* and *The doctor was splashed by the artist*. The task was to read the sentence, press a button to terminate the sentence and initiate the presentation of a question (such as *or Who did the splashing? – the doctor or the artist*), and press one of two buttons to signal the answer. There were 35 active and 35 passive sentences; five sentences of the same type were presented successively in a single epoch. In addition, there was a baseline condition in which the participant fixated a fixation point. The participants were run through two studies with the same design, although different sentences. We present the data only for individuals who had acceptably low head motion.

**Distribution of activation.** The same major cortical regions are involved in sentence comprehension for the adults with autism as for the control individuals. The major activation is in the posterior superior and middle temporal region, the inferior frontal region, with additional activation in the DLPFC, the more posterior part of the middle frontal gyrus, and of course, in the visual areas including the primary visual cortex, the ventral extrastriate and inferior temporal regions, and the motor regions (partially associated with eye fixations). Thus, there are no differences between

individuals with autism and controls with respect to which areas activate during sentence comprehension.

Most but not all of the individuals with autism showed the left lateralization of activation that we typically find in right-handed adults. For two individuals, the language activation was right lateralized, and the analysis included these data; thus, the conclusions apply to the language dominant hemisphere. (While the proportion of right-lateralized processing among this sample seems high, the sample size itself is so small it should not be over interpreted.)

**Activation within the language network.** The second key issue concerns the distribution of activation within the language network. We analyzed the relative amount of activation across three main areas (the dominant inferior frontal, posterior superior and middle temporal regions, and dorsolateral prefrontal region) after setting a threshold for each individual such that there was a total of 35 voxels activated in these three areas. The distribution of these 35 voxels turned out to differ for the two groups. Specifically, the individuals with autism had significantly more activation in the temporal region than the controls and less in the inferior frontal (and the activation was similar for DLPFC for both groups for most but not all comparisons). The results were consistent across the two types of sentences (active and passive), and for the two studies. In this limited sample, there is a reliable difference in the relative degree of activation of the inferior frontal and posterior temporal areas. It is possible that the individuals with autism do less semantic processing in the inferior frontal regions, and instead, rely more on the temporal regions.

The difference in the relative amount of activation in inferior frontal gyrus is associated with a difference in the precise location of the activation. There is a suggestion that the autistic individuals show less activation than controls in the anterior, inferior portion of the inferior frontal gyrus (the pars triangularis), but a similar amount in the superior portion. We are still refining and testing the reliability of this subtle difference in the locus of the activation, as well testing various hypotheses about the possible functional significance of the difference.

**Functional connectivity.** The third key issue concerns the functional connectivity among these regions. Our hypothesis was that there might be less coordination between major regions, such as the frontal and temporal regions, for the individuals with autism than for the control individuals. This hypothesis is motivated by the repeated findings that high-functioning autistic individuals show deficits in tasks requiring high-level abstraction, but not in more concrete tasks. We have assessed functional connectivity by examining the correlations in the time

course of the fMRI-measured activation of the voxels both within and between the major regions of interest. To be conservative, we have analyzed the correlations only within sentence-processing epochs, eliminating the data from the fixation epochs. In these analyses, and average time course is computed for one area, and the time course of each voxel of another area is correlated with that average time course. Functional connectivity can be measured as the number of voxels in the second area that are highly correlated (say with  $r > .4$ ) with the average time course, or the mean of the correlations between the voxels in the second area and the average time course computed from the first area. This analysis yields a relatively consistent pattern, regardless of which measure of connectivity is used. As predicted, the functional connectivity between regions is systematically lower for the individuals with autism. Additionally, some of the areas show higher within-area correlations (each voxel is better correlated with the area's average time course) for the individuals with autism than for controls. These results also generalize to a problem-solving task involving a different set of activated areas. In summary, the analysis suggests a different pattern of functional connectivity for the two groups, with lower inter-area connectivity for the networks. This pattern suggests a deficit in the coordination of processing, a deficit that is consistent with the known cognitive deficits of high-functioning individuals with autism.

The theoretical framework we initially presented helped to frame the issues and studies in high-function autism, and the preliminary findings relate directly to the framework: there is no noticeable difference in the constituency of the large scale cortical networks between the high-functioning autistic individuals and the control group. There are differences between the high-functioning autistic individuals and the control group in the way that the workload is distributed among the members of the large scale cortical network; and there appears to be a lower degree of coordination among the members of the network in the high-functioning autistic individuals than in the control group.

How can such brain activation characteristics be related to psychological processes? The finding of lower coordination may be the key. The results show (and everyone knows) that there is more than one way to produce a particular cognitive outcome. In this case, the outcome is the understanding of a sentence. The tasks were constructed to allow comparable cognitive outcomes to occur, and

comprehension accuracy was indeed comparable. However, the results show that systematically different patterns of brain activation led to the comparable outcomes. We can refer to these different patterns as different "strategies" but this labeling, in itself, does not explain the nature or the possible sources of the difference between the groups. We tentatively propose that one key to understanding the difference in the underlying mechanisms lies in the finding of lower functional connectivity in the high-functioning autistic individuals than in the control group. It may be that some biological factor prevents the inter-area collaboration from developing normally, although the individual areas may initially function normally. During the dynamic recruitment of areas to perform new tasks in the course of development, the competition for "most proficient" or "most specialized" may favor the area that is already favored or specialized for performing some other facet of that task, and disfavor another area whose inclusion in the task performance would require inter-area coordination. This scheme would gradually lead to extreme intra-region specialization and unusually low inter-area coordination. This is a large extrapolation from limited fMRI data, but it is consistent with many documented facets of high-functioning autism, some of which we describe below.

**Non-uniform cognitive profiles or relative sparings in autism.** High-functioning adults with autism often show particular asymmetries in cognitive skills. For example, they have better word level decoding skills and certain visuo-spatial skills than age-matched and IQ-matched controls along with poorer linguistic and abstract reasoning skills (Minshew, Goldstein & Siegel, 1997). This asymmetry echoes the striking asymmetry of the profiles reported for the estimated 10% of the autistic population who are savants (Rimland & Fein, 1988). These individuals have truly outstanding talents that are primarily in the domains of music, rote memory, art, word decoding or spelling, math and mechanics, talents that co-exist with marked deficits in abstraction and linguistic comprehension (Aram & Healy, 1988; Huttenlocher & Huttenlocher, 1973; Rimland & Fein, 1988; Siegel, 1994). The music, art, and mnemonic skills are also grounded in the concrete. For example, their artistic skills may involve drawing concrete objects rather than the abstract, conceptual art. The invited inference is that there may be a trade-off between the more concrete skills that reflect the relative over development of some system and the less developed abstraction skills, that may reflect a relative lack of coordination among subsystems, perhaps in addition to other problems.

Developmental disorders, such as autism, provide an important window on neural development by virtue of the

developmental process itself. What makes the domain both so challenging and so central is that it highlights the interdependence of various systems, not simply during adult performance, but pervading development itself. The essential characteristic of development is the imperative to grow. It is quite possible that the hyper-development that occurs in individuals with autism is one such outcome of development. If a system cannot develop normally, it may clear the way for some other system to become “overly” developed. We noted that the asymmetry in the profile is marked in what has been estimated as 10% of the low-functioning children with autism who are savants; the asymmetry is found in high-functioning individuals who are compared to age and IQ matched controls. Thus, the possibility exists that the asymmetry is common to autism, but simply difficult to identify given that there is such large general variation among individuals in the profile of cognitive and social skills. Thus, the suggestion is that the uneven profiles associated with autism may be an exaggeration of the variation in profiles that mark everyone, an exaggeration that is partially a consequence of the developmental growth process as well as their experiences.

Although our results are still at an early stage, the neuroimaging techniques, in combination with simulation modeling and further experimentation, provide a more precise, testable, and therefore potentially useful, analysis of the developmental processes that underlie autism. It may allow us to understand some of the unique strengths that these individuals possess, as well as point toward additional ways to shore up weaknesses.

**Summary.** In this chapter, we have described, in broad outlines, a theoretical picture that is emerging from the functional imaging of the neural systems that subserve high-level cognitive processes. One of the overarching themes to emerge is that the systems are adaptive both over the short term, as a task’s demands change, and over the longer term, as the individual learns and develops. Indeed, the adaptive processes in the case of human cognition, include biological evolution and embryology, as well as learning and development. The centrality of adaptation in the development of complex systems is not an insight that is unique to developmental cognitive neuroscience; the same insight is emerging from research in a variety of disciplines, such as genetics and physics. Indeed, several theorists have proposed that at an abstract level, the development of complex systems shows similarities across all

domains, from the physical ones to the social ones (Holland, 1992, 1995; Kauffman, 1993).

Drawing closer to our home discipline, it is interesting to consider how the current account refines and builds upon the insights of earlier neurologists, including Luria (1966), and a contemporary neurologist, Mesulam (1990), who eloquently elucidated some similar insights. In both cases, much of the insights came from their own meticulous studies with neuropsychological patients, as well as the experimental data of various researchers in the field. Both accounts, and the earlier ones upon which they build, stress the interactivity of various neural systems. Additionally, Luria draws considerable attention to the adaptiveness of physiological systems in general and neural systems in particular.

The fMRI results quantify and further refine these insights. In addition to noting the adaptiveness of a cognitive system, we can observe and measure the dynamic recruitment of cortical areas that underlies the adaptiveness. We can measure changes in activation volume with a particular change in computational demand. We can observe a shift of activation from a damaged area to its contralateral homologue. More generally, fMRI permits a progression from the observation of adaptiveness to the characterization of the underlying mechanism, operating at the level of activation of cortical regions. The early fMRI results begin to bring the mechanisms into relief, but major challenges remain in characterizing the mechanisms of adaptiveness, the dynamics of brain recruitment, in more detail. These mechanisms are likely to be central to development, learning, and adaptation.

Finally, we note Luria’s argument that some of the theoretical confusions in neuroscience have roots that may be partially due to ambiguity in the constructs. Specifically, Luria notes that “function” in psychology does not mean the activity of a particular organ. Rather, function means an organism’s complex adaptive activity, directed toward the performance of some physiological or psychological task; moreover, the activity may be performed in various ways, with the requirements of the organism determining the means of execution. “Functional systems such as these, complex in composition, plastic in the variability of their elements, and possessing the property of dynamic autoregulation, are apparently the rule in human activity” (Luria, p 23). The contribution of fMRI is to give additional substance to these and other abstract ideas about cognition, and to provide an additional opportunity to quantify these features and to study the operating characteristics of the underlying mechanisms.

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## References

- Aram, D. M., & Healy, J. M. (1988). Hyperlexia: A review of extraordinary word recognition. In L. K. Obler, & D. Fein (Eds.), *The exceptional brain: Neuropsychology of talent and special abilities* (pp. 70-102). New York: Guilford Press.
- Booth, J. R., MacWhinney, B., Thulborn, K. R., Sacco, K., Voyvodic, J. T., & Feldman, H. M. (1999). Development of neuro-cognitive networks for sentence comprehension, mental rotation, and verbal generation in normals and children with brain lesions. Manuscript submitted for publication.
- Braver, T., Cohen, J. D., Jonides, J., Smith, E. E., & Noll, D. C. (1997). A parametric study of prefrontal cortex involvement in human working memory. *NeuroImage*, *5*, 49-62.
- Buchel, C., Coull, J. T., & Friston, K. J. (1999). The predictive value of changes in effective connectivity for human learning. *Science*, *283*, 1538-1541.
- Carpenter, P. A., & Just, M. A. (1999). Modeling the mind: Very high-field functional magnetic resonance imaging activation during cognition. In K. R. Thulborn (Issue Ed.), *Topics in magnetic resonance imaging* (Vol. 10 pp. 16-36). Philadelphia, PA: Lippincott, Williams & Wilkins.
- Carpenter, P. A., Just, M. A., Keller, T., Eddy, W. F., & Thulborn, K. R. (1999). Graded functional activation in the visuospatial system with the amount of task demand. *Journal of Cognitive Neuroscience*, *11*, 9-24.
- Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analysis studies*. New York: Cambridge University Press.
- Case, R. (1992). The role of the frontal lobes in the regulation of human development. *Brain and Cognition*, *20*, 51-73.
- Casey, P. J. (1993). "That man's father is my father's son": The roles of structure, strategy, and working memory in solving convoluted verbal problems. *Memory & Cognition*, *21*, 506-518.
- Courchesne, E. (1997). Brainstem, cerebellar and limbic neuroanatomical abnormalities in autism. *Current Opinions in Neurobiology*, *7*, 269-278.
- Elman, J. A., Bates, E. A., Johnson, M. H., Karmiloff-Smith, A., Parisi, D., & Plunkett, K. (1996). *Rethinking innateness: A connectionist perspective on development*. Cambridge, MA: The MIT Press.
- Engelien, A., Silbersweig, D., Stern, E., Huber, W., Doring, W., Frith, C. D., & Frackowiak, R. J. S. (1995). The functional anatomy of recovery from auditory agnosia: A PET study of sound categorization in a neurological patient and normal controls. *Brain*, *118*, 1395-1409.
- Galaburda, A. M., & Rosen, G. D. (in press). Neural plasticity in dyslexia: A window to mechanisms of learning disabilities. To appear in J. L. McClelland, & R. S. Siegler (Eds.), *29th Carnegie Symposium on Cognition: Mechanisms of cognitive development: Behavioral and neural perspectives*. Mahwah, NJ: Erlbaum.
- Gardner, H. (1983). *Frames of mind: The theory of multiple intelligence*. New York: Basic Books, Inc.
- Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston, MA: Houghton Mifflin.
- Goldstein, G., Minshew, N., & Siegel, D. (1994). Age differences in academic achievement in high-functional autistic individuals. *Journal of Clinical and Experimental Neuropsychology*, *16*, 671-680.
- Goodman, R. (1994). Brain disorders. In M. Rutter, E. Taylor, & L. Hersov (Eds.), *Child and adolescent psychiatry: Modern approaches* (3 ed., pp. 569-593). London: Blackwell.
- Goodman, R. (1989). Infantile autism: A syndrome of multiple primary deficits? *Journal of Autism and Developmental Disorders*, *19*, 409-424.
- Grandin, T. (1995). *Thinking in pictures: And other reports from my life with autism*. New York: Doubleday.
- Grandin, T., & Scariano, M. (1986). *Emergence: Labeled autistic*. Novato, CA: Arena Press.
- Grasby, P. M., Frith, C. D., Friston, K. J., Simpson, J., Fletcher, P. C., Frackowiak, R. S. J., & Dolan, R. J. (1994). A graded task approach to the functional mapping of brain areas implicated in auditory-verbal memory. *Brain*, *117*, 1271-1282.
- Haarmann, H. J., Just, M. A., & Carpenter, P. A. (1997). Aphasic sentence comprehension as a resource deficit: A computational approach. *Brain and Language*, *59*, 76-120.
- Hebb, D. O. (1949). *Organization of behavior*. New York: Wiley.
- Holland, J. H. (1992). *Adaptation in natural and artificial systems: An introductory analysis with applications to biology, control, and artificial intelligence*. Cambridge, MA: The MIT Press.
- Holland, J. H. (1995). *Hidden order: How adaptation builds complexity*. Reading, MA: Addison-Wesley.
- Howe, M. J. A. (1989). *Fragments of genius: The strange feats of Idiots Savants*. New York: Routledge.
- Hughes, C. (1996). Brief report: Planning problems in autism at the level of motor control. *Journal of Autism and Developmental Disorders*, *26*, 99-107.



Hughes, C., Russell, J., & Robbins, T. W. (1994). Evidence for executive dysfunction in autism. *Neuropsychologia*, 32, 477-492.

Huttenlocher, P. R., & Huttenlocher, J. (1973). A study of children with hyperlexia. *Neurology*, 23, 1107-1116.

Johnson, M. H. (1997). *Developmental cognitive neuroscience: An introduction*. Cambridge, MA: Blackwell Publishers, Inc.

Just, M. A., & Carpenter, P. A. (1992). A capacity theory of comprehension: Individual differences in working memory. *Psychological Review*, 99, 122-149.

Just, M. A., & Carpenter, P. A. (1985). Cognitive coordinate systems: Accounts of mental rotation and individual differences in spatial ability. *Psychological Review*, 92, 137-172.

Just, M. A., & Carpenter, P. A. (1993). The intensity of thought: Pupillometric indices of sentence processing. *Canadian Journal of Experimental Psychology*, 47, 310-339.

Just, M. A., Carpenter, P. A., Keller, T. A., Eddy, W. F., & Thulborn, K. R. (1996). Brain activation modulated by sentence comprehension. *Science*, 274, 114-116.

Just, M. A., Carpenter, P. A., & McNeil, M. (1999). Neurocognitive remediation of aphasic language understanding. Unpublished manuscript, Carnegie Mellon University, Center for Cognitive Brain Imaging, Pittsburgh, PA.

Just, M. A., Carpenter, P. A., & Varma, S. (1999). Computational modeling of high-level cognition and brain function. *Human Brain Mapping*.

Kauffman, S. A. (1993). *The origins of order: Self-organization and selectin in evolution*. New York: Oxford University Press.

Keller, T. A., Carpenter, P. A., & Just, M. A. (1999). The neural basis of sentence comprehension: fMRI examination of syntactic and lexical processing. Unpublished manuscript, Carnegie Mellon University, Center for Cognitive Brain Imaging, Pittsburgh, PA.

King, J., & Just, M. A. (1991). Individual differences in syntactic processing: The role of working memory. *Journal of Memory and Language*, 30, 580-602.

Kwong, K. K., Belliveau, J. W., Chesler, D. A., Goldberg, E. I., Weisskoff, R. M., Poncelet, B. P., Kennedy, D. N., Hoppel, B. E., Cohen, M. S., Turner, R., Cheng, H. M., Brady, T. J., & Rosen, B. R. (1992). Dynamic magnetic resonance imaging of human brain activity during primary sensory stimulation. *Proceedings of the National Academy of Science, USA*, 89, 5675-5679.

Luria, A. R. (1966). *Higher cortical functions in man: Second Edition Revised and Expanded*. New York: Basis Books, Inc.

McClelland, J. L., Rumelhart, D. E., & The PDP Research Group. (1986). *Parallel distributed processing:*

*Explorations in the microstructures of cognition Volume 2: Psychological and biological models*. Cambridge, MA: MIT Press.

Mesulam, M.-M. (1990). Large-scale neurocognitive networks and distributed processing for attention, language and memory. *Annals of Neurology*, 28, 597-613.

Michaels, E., Just, M. A., Keller, T. A., & Carpenter, P. A. (1999). An fMRI comparison of visual and auditory sentence comprehension. Unpublished manuscript, Carnegie Mellon University, Center for Cognitive Brain Imaging, Pittsburgh, PA.

Minshew, N. J. (1996). Autism. In B. O. Berg (Ed.), *Principles of child neurology* (pp. 1713-1729). New York: McGraw-Hill.

Minshew, N. J., Goldstein, G., Dombrowski, S. M., Panchalingam, K., & Pettegrew, J. W. (1993). A preliminary <sup>31</sup>P MRS study of autism: Evidence for undersynthesis and increased degradation of brain membranes. *Biological Psychiatry*, 33, 762-773.

Minshew, N. J., Goldstein, G., & Siegel, D. J. (1997). Neuropsychologic functioning in autism: Profile of a complex information processing disorder. *Journal of the International Neuropsychological Society*, 3, 303-316.

Minshew, N. J., Goldstein, G., & Siegel, D. J. (1995). Speech and language in high-functioning autistic individuals. *Neuropsychology*, 9, 255-261.

Neville, H. J. (1993). Neurobiology of cognitive and language processing: Effects of early experience. In M. H. Johnson (Ed.), *Brain development and cognition: A reader* (pp. 424-448). Cambridge, MA: Blackwell Publishers, Inc.

Nicolelis, M. A. L. (1997). Dynamic and distributed somatosensory representations as the substrate for cortical and subcortical plasticity. *Seminars in Neurobiology*, 9, 24-33.

Ogawa, S., Lee, T. M., Kay, A. R., & Tank, D. W. (1990). Brain magnetic resonance imaging with contrast dependent on blood oxygenation. *Proceedings of the National Academy of Science, USA*, 87, 9868-9872.

Ozonoff, S. (1995). Executive functions in autism. In E. Schopler, & G. B. Mesibov (Eds.), *Learning and cognition in autism* (pp. 199-219.). New York: Plenum Press.

Ozonoff, S., & McEvoi, R. E. (1994). A longitudinal study of executive function and theory of mind: Development in autism. *Development and Psychopathology*, 6, 415-431.

Ozonoff, S., Pennington, B. F., & Rogers, S. J. (1991). Executive function deficits in high-functioning autistic individuals: Relationship to theory of mind. *Journal of Child Psychology and Psychiatry*, 32, 1081-1105.

Ozonoff, S., Strayer, D. L., McMahon, W. M., & Filloux, F. (1994). Executive function abilities in autism and Tourett syndrome: An information processing approach. *Journal of Child Psychology and Psychiatry*, 35, 1015-1032.

Parks, R. W., Lowenstein, D. A., Dodrill, K. L., Barker, W. W., Yoshii, F., Chang, J. Y., Emran, A., Apicella, A., Sheramata, W. A., & Duara, R. (1988). Cerebral metabolic effects of a verbal fluency test: A PET scan study. *Journal of*

*Clinical and Experimental Neuropsychology*, 10, 565-575.

Petitto, L. A. (1996). In the beginning: On the genetic and environmental factors that make early language acquisition possible. In M. Gopnik, & S. Davis (Eds.), *The genetic basis of language*. Hillsdale, NJ: Erlbaum.

Piaget, J., & Inhelder, B. (1969). *The psychology of the child*. New York: Basic Books, Inc.

Rimland, B., & Fein, D. (1988). Special talents of autistic Savants. In L. K. Obler, & D. Fein (Eds.), *The exceptional brain: Neuropsychology of talent and special abilities* (pp. 474-492). New York: Guilford Press.

Rumsey, J. M. (1985). Conceptual problem-solving in highly verbal, nonretarded autistic men. *Journal of Autism and Developmental Disorders*, 15, 23-36.

Rumsey, J. M., & Hamburger, S. D. (1988). Neuropsychological findings in high-functioning autistic men with infantile autism, residual state. *Journal of Clinical and Experimental Neuropsychology*, 10, 201-221.

Sanes, J. M., & Donoghue, J. P. (1997). Dynamic motor cortical organization. *The Neuroscientist*, 3, 158-165.

Sanes, J. N., & Donoghue, J. P. (1997). Static and dynamic organization of motor cortex. *Advances in Neurology*, 73, 277-296.

Sanes, J. N., Donoghue, J. P. T. V., Edelman, R. R., & Warach, S. (1995). Shared neural substrates controlling hand movements in human motor cortex. *Science*, 268, 1775-1777.

Schwartz, M. F., Saffran, E. M., Fink, R. B., Myers, J. L., & Marin, N. (1994). Mapping therapy: A treatment program for agrammatism. *Aphasiology*, 8, 19-54.

Selge, L. (1977). *Nadia: A case of extraordinary drawing ability in an autistic child*. London, UK: Academic Press.

Siegel, D. J., Minshew, N. J., & Goldstein, G. (1996). Wechsler IQ profiles in diagnosis of high-functioning autism. *Journal of Autism and Developmental Disorders*, 26, 389-406.

Siegel, L. S. (1994). The modularity of reading and spelling: Evidence from hyperlexia. In G. D. A. Brown, & N. C. Ellis (Eds.), *Handbook of spelling: Theory, process and intervention* (pp. 227-248). Sussex, UK: Wiley.

Stiles, J., & Thal, D. (1993). Linguistic and spatial cognitive development following early focal brain injury: Patterns of deficit and recovery. In M. H. Johnson (Ed.), *Brain development and cognition: A reader* (pp. 643-664). Cambridge, MA: Blackwell Publishing, Inc.

Thatcher, R. W. (1992). Cyclic cortical reorganization during early childhood. *Brain and Cognition*, 20, 24-50.

Thulborn, K. R., Carpenter, P. A., & Just, M. A. (1999). Plasticity of language-related brain function during recovery from stroke. *Stroke*, 30, 749-754.

Weiller, C., Isensee, C., Rijntjes, M., Huber, W., Muller, S., Bier, D., Dutschka, K., Woods, R. P., Noth, J., & Diener, H. C. (1995). Recovery from Wernicke's aphasia: A positron emission tomographic study. *Annals of Neurology*, 37, 723-732.