

A Critical Review of PET Studies of Phonological Processing

DAVID POEPPEL

Department of Brain and Cognitive Sciences, Massachusetts Institute of Technology

The use of positron emission tomography to identify sensory and motor systems in humans in vivo has been very successful. In contrast, studies of cognitive processes have not always generated results that can be reliably interpreted. A meta-analysis of five positron emission tomography studies designed to engage phonological processing (Petersen, Fox, Posner, Mintun, & Raichle, 1989; Zatorre, Evans, Meyer, & Gjedde 1992; Sergent, Zuck, Levesque, & MacDonald, 1992; Demonet, Chollet, Ramsay, Cardebat, Nespoulous, Wise, & Frackowiak, 1992; and Paulesu, Frith, & Frackowiak, 1993) reveals that the results do not converge as expected: Very similar experiments designed to isolate the same language processes show activation in nonoverlapping cortical areas. Although these PET confirm the importance of left perisylvian cortex, the experiments implicate distinct, nonoverlapping perisylvian areas. Because of the divergence of results, it is premature to attribute certain language processes or the elementary computations underlying the construction of the relevant linguistic representations to specific cerebral regions on the basis of positron emission tomographic results. It is argued that this sparse-overlap result is due (1) to insufficiently detailed task decomposition and task-control matching, (2) to insufficient contact with cognitive psychology, psycholinguistics, and linguistic theory, and (3) to some inherent problems in using subtractive PET methodology to study the neural representation and processing of language. © 1996 Academic Press, Inc.

1. INTRODUCTION

The harnessing of positron emission tomography (PET) as an experimental tool for cognitive neuroscience has generated much enthusiasm. The method

For their various forms of help, including critical comments on the paper and telling me when and about what I am misguided, I am indebted to Kevin Broihier, David Caplan, Suzanne Corkin, John Kim, Gary Marcus, Steven Pinker, Amy Mitchell Poeppel, Ernst Pöppel, and Kenneth Wexler. I am also grateful for the detailed constructive suggestions of the anonymous reviewers. During the preparation of the manuscript, the author was supported by the McDonnell-Pew Center for Cognitive Neuroscience at MIT. Address correspondence and reprint requests to David Poeppel, Biomagnetic Imaging Laboratory, University of California at San Francisco, 513 Parnassus, S-362, San Francisco, CA, 94143-0628. E-mail: poeppel@itsa.ucsf.edu.

has been applied to domains ranging from vision, motor control, attention, and memory to less typical research areas like musical cognition (Sergent et al., 1992) and olfaction (Zattore et al., 1992). The results are argued to provide the underlying functional neuroanatomy of a given sensory, motor, or cognitive process as well as imposing crucial constraints on the formulation of theories explaining the function under consideration (cf. Posner, Petersen, Fox, & Raichle, 1988; Posner, Sandson, Dhawan, & Shulman, 1989). Experiments using PET constitute an enormous new source of data on in vivo functional neuroanatomy and have received considerable support (for enthusiastic reviews see, among others, Crease, 1993; Haxby, Grady, Ungerleider, & Horwitz, 1991; Kandel, Schwartz, & Jessel, 1991; Posner & Raichle, 1994). Recently, though, more cautious assessments, particularly with respect to studies of cognitive processes including language processing have appeared as well (Chertkow & Bub, 1994; Demonet, Wise, & Frackowiak, 1993; Frackowiak, 1994; Petersen & Fiez, 1993; Sergent, 1994; Stowe, Wijers, Willemsen, Reuland, Paans, & Vaalburg, 1994).

Non-invasive brain imaging methods like PET (and the even more recent development of functional magnetic resonance imaging) are particularly exciting for the investigation of the domains of human cognition for which there are no animal models. One goal therefore is to use PET to investigate the cortical (and subcortical) organization and representation of language. Our state-of-the-art map of where language is processed in the brain has derived largely from the results of documenting and cataloguing deficit-lesion correlations (for review see, for example, Caplan, 1992). Functional neuroimaging methods like PET complement the deficit-lesion correlation approach by providing a way to investigate the intact brain at work. This review examines some studies of phonological language processing and questions whether we are in a position to update or revise our map of language in the brain on the basis of PET studies.

The successful use of PET technology in the study of cognitive processes demands that experiments designed to isolate the same cognitive process or elementary mental computation also implicate the same neural substrate. The practical consequence is that the results should *overlap* in some meaningful way. Concretely, if an experiment implicates some cerebral area or set of areas in some cognitive process, a different experiment investigating the same cognitive process should implicate at least some of the areas of the first study. The desideratum is, of course, that the same cerebral region or set of regions will reliably be implicated across experiments when the same cognitive process (or *cognitive module* or *computational subroutine*) is selectively engaged.

The comparison of five PET studies designed to selectively engage phonological processing shows that the results do not overlap as one might expect: The brain areas implicated in the computation of phonetic and phonological representations are different for each study. Interestingly, all the studies are

able to adduce deficit-lesion correlation evidence consistent with each finding. That is, *five studies on phonological processing generated five different findings*—and these in turn are consistent with five different sources of evidence from the deficit-lesion correlation literature. We are therefore not yet in a position to attribute phonetic or phonological processing (or the elementary processes underlying the construction of the relevant representations) to specific regions of the brain on the basis of PET studies.

I argue that this *no-overlap* or *sparse-overlap* result for the domain of phonological processing is a consequence of the lack of contact with the analytic machinery of cognitive psychology, psycholinguistics, and linguistic theory. From the point of view of information-processing psychology, the decomposition of the experimental tasks used is not sufficiently explicit. Since the goal of the experiments is the isolation of a specific cognitive computation, a detailed task analysis and decomposition would aid in constraining how the experimental and subtracted control conditions are set up and how the results can be interpreted. Moreover, if the experiments are such that the cognitive computations supposedly invoked do not stand in any straightforward relationship with facts about language and language processing that we know independently (say, from psychology, psycholinguistics, or linguistic theory), the interpretation of the data is severely underconstrained. Implicit in the review, then, is the suggestion that a more directed effort at contact with disciplines that study language might be useful for future experiments investigating the neural basis of language.

2. PRELIMINARIES

2.1 *The Paired-Image Subtraction Paradigm*

Cerebral activity as reflected by the neural discharge rate in the brain is coupled to changes in regional cerebral blood flow (rCBF) and several other physiological factors, including cerebral blood volume, glucose utilization, and the oxygenation of hemoglobin. (For methodological details and for an explanation of the technical aspects of positron emission tomography, see Roland, 1993. For a more conceptual and less technical introduction see Posner and Raichle, 1994.) PET studies take advantage of the fact that increased activity in an area is coupled to increased regional blood flow. Because PET depends on blood flow dynamics, the temporal resolution of positron emission tomography is low. At present, the fastest image acquisition time is greater than ten seconds (Demonet et al., 1993). Because the cognitive processes at stake in language processing are at least an order of magnitude faster (in the range of tens of milliseconds) and because the physiological indices of activity correlated with a task may be very weak, special analytic strategies have been developed in order to obtain activation images with adequate signal-to-noise ratios. One popular approach involves subtracting activation images generated during experimental and control conditions from

one another. Stimuli are presented in blocks of the same stimulus type to attempt to ensure homogeneity of cognitive activation and neuronal activation, and the post-processing of the acquired images entails *intrasubject* subtraction and *intersubject* averaging (Fox, Mintun, Reiman, & Raichle, 1988).

In the subtractive method (used in all the experiments discussed in this article) images are acquired during the performance of two (sometimes nested) tasks, a putatively simpler task A and a more complex task B (the tasks are simple or complex relative to each other; there is no absolute measure of complexity involved). The optimal tasks are *minimally* different and are, ideally, in a subset relation, such that a more elaborate Task B encompasses all the components (and, by assumption, the relevant cortical areas) used in the less elaborate Task A. Suppose experimental task A recruits n cognitive components and the image taken during performance of task A shows m neural components. By assumption, task B recruits $(n + x)$ cognitive components and the image acquired during performance of B shows $(m + y)$ cerebral areas of activation. Subtraction of image A from image B yields an ideally small number of cerebral areas (y). These are argued to be the neural substrate for exactly those computations that differ between tasks A and B, specifically the factor x , whatever that may be. It is intuitively clear that the method mandates a very close match between test and control conditions to generate interpretable results. Note that there are a number of problematic assumptions built into this methodology; these are discussed in section 4. The logic and limitations of the subtractive method are also discussed for PET studies by Chertkow and Bub (1994), Posner et al. (1988), Raichle, Fiez, Videen, MacLeod, Pardo, Fox, & Petersen (1994), and Sergent et al. (1992), and, as a more general issue in experimental psychology by Sternberg (1969).

2.2 Selection of Studies for Review

The selection criteria for inclusion of the studies are straightforward. All the studies investigate phonetic/phonological processing and they all articulate a specific claim about the cerebral localization of phonological processing based on similar experimental paradigms.¹ Specifically, the studies reviewed here use rhyme judgments to engage phonological processing. Za-

¹ Because functional neuroimaging research is rather new, it is possible to compare all the major PET research papers on phonological processing that have appeared in the literature in the last few years. Insofar as this literature expands, one will want to develop formal criteria when including studies in a meta-analysis. There are, in fact, several directly relevant neuroimaging studies that are not included in the comparison developed in section 3. These papers are either newer (Fiez et al., 1995), use a different experimental paradigm (Mazoyer et al., 1993), or use a different neuroimaging technique (Shaywitz et al., 1995). Because these articles make claims germane to the argument presented in the review, they are discussed in Section 4.3.

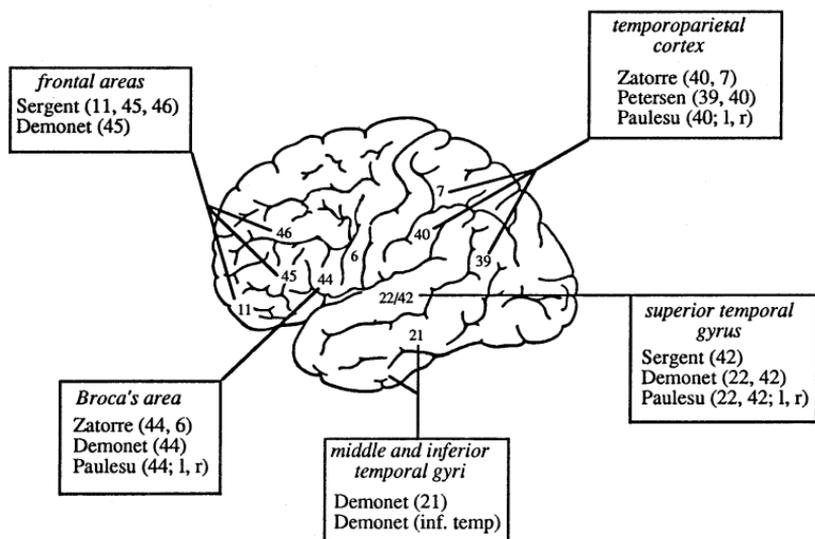


FIG. 1. The no-overlap/sparse-overlap results for phonological processing. The cortical areas depicted in the figure are argued to mediate phonetic and phonological processing in the five studies reviewed. The areas are indicated by Brodmann number and verbal labels, as in the papers. The names of authors associated with a particular area indicate which cortical regions are considered crucial by each research group for the performance of the experimental task in particular, and phonological processing in general.

torre et al. (1992) asked subjects to compare and judge as same or different the final consonants in auditorily presented pairs of consonant-vowel-consonant (CVC) strings. Sergent et al. (1992) required a rhyme judgment on single visual letters rhyming with /i/, while Paulesu et al. (1993) combined that same task with a short-term letter memory task to isolate phonological processing. The study by Petersen, Fox, Posner, Mintun, and Raichle (1989) required a rhyme judgment on visual word-pairs. Finally, Demonet et al. (1992) used a phonetic monitoring task in which the subject had to detect a [b] in a non-word. Four of the 5 studies required subjects to make a yes/no judgment about the end of a phonetic string. Because making that type of judgment is—at least by hypothesis—dependent of the modality of stimulus presentation, one would expect to see relatively similar results.

A comparison of areas showing rCBF increase reveals that the results are not only different but *nonoverlapping*. There is no single area that is consistently implicated across the five studies on phonetic/phonological processing. In fact, no area is implicated in more than three experiments. I call this the *no-overlap result*. This meta-analytic observation suggests that PET studies on phonological processing to date are contradictory. Fig. 1 summarizes schematically the results of the five studies exploring phonetic/phonological processing discussed in this chapter. In what follows, I summarize

TABLE 1
Five Experiments on Phonological Processing

Study	Stimulus type	Stimulus modality	<i>N</i> (subjects); gender; handedness	Stimulus rate ^a
A. Zatorre et al.	Word and non-word pairs (CVCs)	Auditory	10; 5 female, 5 male; Right Handers	14–18/min
B. Petersen et al.	Word pairs	Visual	7; not available; RH	48/min
C. Sergent et al.	Single letters (consonants)	Visual	8; male; RH	20/min
D. Demonet et al.	Non-words	Auditory	9; male; RH	20/min
E. Paulesu et al.	Single letters (consonants)	Visual	6; male; RH	60/min

^aThe stimulus rates that were not explicitly given in stimuli/min were reconstructed from information available in the paper; this was unproblematic because sufficient information was always there.

the experiments and analyze the no-overlap finding. Tables 1, 2, and 3 contain the relevant details about the experiments.

3. A COMPARISON OF PET STUDIES OF PHONOLOGICAL PROCESSING

3.1 Zatorre, Evans, Meyer, and Gjedde (1992)

The experiment tested which cortical areas are responsive to nonspeech auditory stimulation and to auditorily presented word and pseudo-word consonant-vowel-consonant (CVC) strings. The experimental parameters are summarized in Tables 1A and 2A. The nonspeech stimuli consisted of pairs of noise-bursts; the speech stimuli were CVC pairs, half of which were words and half of which were pseudo-words (possible words). In the relevant condition, subjects heard CVC pairs and had to judge whether the final consonant was the same or different. The control condition used for subtraction was a “passive listening condition” in which subjects were presented with pairs of CVCs to which they had to attend but not generate a response. Note that the stimulus set for both conditions was identical. The cognitive operation putatively isolated by this subtraction is called “phonetic processing.”

Table 3A lists all areas which showed significant signal increase in the phonetic judgment condition, after subtraction of the condition in which CVC pairs were heard passively. Special importance is attributed to the activation foci in the frontal lobe (44, 6) and the parietal lobe (7, 40).

The authors’ interpretation of the findings centers on the observation that a significant local increase in blood flow was recorded around Broca’s area in the left hemisphere in the phonetic condition, with an additional focus in the left temporo-parietal region. They argue that lesions in and around Bro-

ca's area typically result in nonfluent aphasia and articulatory disorders but also in phonetic perceptual deficits (see, e.g., Blumstein, Baker, & Goodglass, 1977). They propose that "in making the phonetic judgment, subjects must access an articulatory representation involving neural circuits that include Broca's area" (Zatorre et al., 1992, p. 848). The authors explicitly assume the framework of the motor theory of speech perception (Liberman and Mattingly, 1985), and hypothesize that Broca's area is crucially involved in the reconstruction of the intended articulatory gestures that are necessary for speech perception. They point out that the focus in left parietal lobe is relevant as well. In the conclusion they "suggest that phonological processing is accomplished through a network including the left posterior temporal and parietal regions as well as Broca's area, although each region's precise contribution remains to be elucidated" (Zatorre et al., 1992, p. 848).

Can one persuasively argue on the basis of the experimental tasks and the subtraction performed that (some aspect of) phonological processing has been isolated? First, let us make explicit what goes into the execution of the task, i.e., the task decomposition. The experimental task entails a number of components, and a subject has to accomplish at least the following subroutines in the experimental condition: remembering the instructions of the task, listening to and remembering a pair of CVC strings, decomposing the strings (minimally into an onset and a final consonant each), comparing two final consonants, and selecting a response. These components, in turn, can likely be broken down into even finer-grained subcomputations. It is clear that phonetic/phonological processing comes into play insofar as the task involves speech input and because the task involves making judgments on auditorily presented word and pseudo-word letter strings. However, it is not immediately obvious that the task and subtraction isolate phonological processing. Listeners typically do not break down the speech stream into pairs of temporally adjacent CVC strings or even temporally adjacent words, remember them, and maintain them in a format that encourages the comparison of two particular segments in the pair. There is also no special reason in spoken language to attend exclusively to the final consonant of any given pair. In other words, although the task does require that the subject make contact with particular phonological representations, the task also has very specific and unusual task demands that presumably play a significant role in the execution of the experiment and for the interpretation of the results.

Second, consider along what dimensions the test condition differed from the control: In the "passive speech" condition (see Table 2A) subjects were instructed to do nothing but press a key to every CVC pair, alternating between yes and no responses. To what extent subjects actually processed each CVC pair is not determined. The control condition is, therefore, underconstrained relative to the test condition, and consequently we cannot know how extensively subjects do process the stimuli in the "passive" condition. Subjects may automatically make a word versus non-word judgment, access

TABLE 2
Experimental Designs

Condition	Stimulus	Response	Example	Isolated process (test condition subtracted)
A. Zatorre et al. Baseline Noise	Silence Noise burst pairs	None Alternating keypress		Primary sensory proc. (silence)
Passive speech	Consonant-vowel-cons. pairs	Alternating keypress	fat-tid (Yes) tig-lat (No) bag-big (Yes)	Passive sens. proc. of CVCs (noise)
Phonetic	CVC pairs	Keypress to same final consonant-rhyme	fat-tid (N) tig-lat (N) bag-big (Y)	Phonetic processing (passive CVCs)
B. Petersen et al. Rhyme	Word pairs	Keypress to rhyme	dog-bog (Y) dog-cat (N)	Phon. encoding (same stim- uli, no response)
C. Sergent et al. Fixation Object task	Fixation point Line drawings (living ver- sus non-living)	None Keypress to category		Categorization (a. letter- spatial b. letter-sound)

Letter (spatial)	Capitalized consonants	Keypress to orientation	G (Y) mirror-G (N) F (Y) F (N) J (N) D (Y)	Spatial proc. (a. object b. letter-sound)
Letter (sound)	Capitalized consonants	Keypress to rhyme		Phonolog. proc. (a. object b. letter-spatial)
D. Demonet et al.				
Tone task	Triplets of pure tones	Keypress to target	target: 500-500-1000 (Hz) distractor: 500-500-500	Early acoustic processing
Phonemes task	Non-words (3-4 syllables)	Keypress to target	tar: redozabu dis: zotabive	Phonological processing (tone task)
Words task	Adjective-noun pairs	Keypress to target	tar: kind mouse dis: horrible horse	Semantic processing (tone task)
E. Paulesu et al.				
Rhyming task (phonological similarity)	Single consonants	Pos. response to rhyme (with 'B')	G (Y) M (N)	Subvoc. rehearsal (shape, similarity)
Phonological memory task	String of six dissimilar consonants	Pos. response to probe-stim. set match	Stim: k-l-m-p-q-d resp: no	Phon. storage (visual memory)

TABLE 3
 Areas Showing rCBF Increase in Five Experiments on Phonological Processing^a (All areas listed are in the left hemisphere, unless otherwise noted.)

A. Zatorre et al.	B. Petersen et al.	C. Sergent et al.-a	C. Sergent et al.-b	D. Demonet et al.	E. Paulesu et al.
Phonetic condition minus passive CVCs	Judgment minus passive word pairs	Letter sound minus letter spatial	Letter-sound minus objects	Phoneme-task minus tones task	Rhyming judgment for letters
Area (name or Brodmann number)	Area (name or Brodmann number)	Area (name or Brodmann number)	Area (name or Brodmann number)	Area (name or Brodmann number)	Area (name or Brodmann number)
• 44/6	• 39/40 ^b	• 46	• 45	• sup. temporal gyr ^c (BA 42, 22)	• SMA (left and right)
• 31 midline	• caudate nucleus	• 42	• 42	• middle temporal gyr (BA 21)	• 44 (l,r)
• 17 (right)	• 11	• 11	• 11	• inf. temporal gyr and fusiform gyr	• 40 (l,r)
• 7/40	• 45	• 45	• 6/8	• middle temporal gyr (right)	• 22/42 (l,r)
• 24 (midline)	• 21	• 21	• 46	• Broca's area (44)	• 18
• 20			• 24 (right)	• ant. to Broca's (45)	• insula (l,r)
					• cerebellum (l,r)

^a Note that results obtained with positron emission tomography are reported in a standardized coordinate system (Tallarach & Tournoux, 1988); the names of regions and the corresponding designation of Brodmann's areas merely serve as mnemonics.

^b The condition was run as a control, and there are no other data available on which areas were activated during the task.

^c Excluding primary auditory cortex.

lexical-semantic information, activate associated lexical entries, and so on. The test condition makes a very specific attentional demand (discriminate along a particular phonological dimension). Subjects not only have to remember the (relatively more detailed) instructions *and* any given CVC pair, but also maintain it in a format that allows comparison of the final consonants (something like short-term verbal working memory with an articulatory loop; cf. Baddeley, 1992).

A straightforward alternative interpretation of the results is possible (including a plausible reinterpretation of the function of Broca's area) given that the most salient difference between test and control conditions is the fact that subjects had to remember each given pair in the test condition. Rather than mediating some aspect related to articulatory representations, one could argue that the anterior areas reported are crucial for some aspect of short-term verbal memory (say, for instance, subvocal rehearsal). And the reason those areas show a local blood-flow increase in the test relative to the control condition is that the execution of the task requires the selective engagement of verbal working memory.²

3.2 Petersen, Fox, Posner, Mintun, and Raichle (1989)

The experimental contrast on which Petersen et al. base their case about possible neural sites of phonological processing was one of a number of conditions in a large experiment. The experiment is arguably the most well-known PET study and the first to seriously study verbal cognitive processes. Because the part of the experiment discussed in this review served primarily as an additional control condition, there is less information available. Nevertheless it is worthwhile examining the claims set forth, first because the authors make a specific proposal about the localization of an aspect of phonological processing (phonological encoding), and second because the task is comparable to the other experimental tasks discussed in this paper in that subjects were required to make rhyme judgments.

Tables 1B and 2B summarize the experimental parameters. In the test condition, subjects were presented visually with two words, one above and one below a fixation point. The required response was a yes/no rhyme judgment, and the presented pairs consisted of rhyming or nonrhyming, visually similar or dissimilar words. In the control condition, subjects were presented with the same stimulus set but had to maintain fixation and generate no response.

² This view is, in fact, consistent with the interpretation that Paulesu et al. (1993) have for the activation of Broca's area. Moreover, Awh et al. (1994) have substantiated that result in an experiment designed to engage components of working memory. Both groups conclude that verbal short-term memory (probably the rehearsal aspect) is mediated by Broca's area and that (what in Baddeley's model is called) phonological encoding selectively activates parietal areas around areas 7 and 40.

Although a number of areas showed an increase in regional cerebral blood flow in the task under consideration (see Figs. 2E,F in Petersen et al., 1989), the authors focus on one particular region. Based on a separate condition investigating auditory processing, they consider three candidate areas for phonological processing: anterior superior temporal cortex, temporoparietal cortex, and lateral temporal cortex. The region showing activation in the rhyme judgment task (after subtraction) is in left temporoparietal cortex. They adduce supporting lesion evidence that suggests that temporoparietal cortex may mediate this type of phonological processing or encoding (Roeltgen, Sevush, & Heilman, 1983; Shallice, 1981).

Consider the decomposition analysis for this experiment: In what way does the experimental task recruit phonological knowledge? The tachistoscopic presentation of two lexical items in a vertical array by itself does not constitute a typical language processing computation because readers do not make rhyme judgments on pairs of words presented above each other at 250ms exposure. What language-specific and general nonlinguistic computations do go into the experimental task and may therefore account for the activations? First, subjects have to parse the visual scene into written words, perhaps consulting an iconic memory representation because of the brief exposure of the stimuli and the noncanonical arrangement of the written words. This process, naturally, has a number of subcomponents, all of which may also be part of the control task. Subsequently, at least the following computations have to occur: (1) grapheme to phoneme recoding, (2) whatever processing occurs automatically in word recognition, (3) recollection/reactivation of the task demands, (4) consultation of the phonological representation relevant to the execution of the task, (5) comparison of the two words, and (6) selection/generation of the response. The selection or activation of the representation relevant to the comparison itself entails a number of components; minimally, some contact must be made with articulatory representations, since the rhyme judgment presumably requires either auditory input or reference to an articulatory representation that either generates or allows access to the sound of the rhyming pair. Notice that most of these computations are unique to the test condition, and therefore presumably they do not subtract out.

Second, consider whether test and control conditions are closely matched. The subjects did not have to provide any response in the control condition. Rather, subjects fixated while the same words were presented in the vertical array. This constitutes a good control for the visual aspect of the task, since everything in the tasks was identical from that point of view, and one would expect that the visual activation across conditions subtracts out (as it appeared to do). However, one cannot ascertain that subjects did not engage in any type of phonological judgment/task during the control condition. Because no response was required, subjects' behavior was unconstrained in the control task, which means that one cannot rule out phonological processing

of the stimuli in that condition. In fact, the interpretation crucially depends on one's model of language processing. On some accounts (cf. Foder, 1983), the null hypothesis is that a language stimulus (e.g., a visually presented word) is processed automatically along a variety of dimensions, including an item's grammatical category, phonological form, similarity to items stored "nearby" in the mental lexicon, and so on. On such a view one might argue that—because subjects were not prevented from computing a phonological representation—they computed at least some aspect of a phonological representation automatically. Consequently, the difference between test and control might not isolate the phonological aspect of processing sufficiently; rather, the attentional modulation of phonological processing is engaged. A final concern is that other linguistic representations (e.g., grammatical category, items nearby in the mental lexicon, etc.) also enter into the computational system even if they are not germane to the specific experimental task. These issues illustrate clearly how even in an experiment in which test and control conditions are very tightly matched the interpretation of the results is conditioned by the *specific model of language* one subscribes to, independent of the experimental data.

3.3 *Sergent, Zuck, Levesque, and MacDonald (1992)*

Sergent et al.'s experiment is a response to the studies by Zatorre et al. (1992) and Petersen et al. (1988, 1989). Sergent et al. suggest that in order to isolate a particular linguistic code one should use stimuli that are not susceptible to interference from other (linguistic) codes. Therefore they used visual letters as stimuli, arguing that one can isolate the visual and phonological "codes" of a letter without interference from semantic, lexical, orthographic, or syntactic codes. One of the central goals of the experiment was to isolate the cerebral loci underlying phonological processing and to replicate the results described in the studies by Zatorre et al. (1992) and Petersen et al. (1989).

The stimuli used in this assessment of phonological processing were distributed among a test condition and two control conditions used for subtraction (see Tables 1C and 2C for summary of the relevant parameters). The main experimental condition, the letter-sound task (see Table 2C) was a rhyme judgment (does the presented letter rhyme with /i/) on individually presented visual letters. There were two control (subtraction) conditions. In one of the controls, an *object task*, the stimulus set consisted of 24 line-drawing objects, half of which were living, and half of which were nonliving. The task was a forced-choice categorization along the "living" dimension. The second control, a *letter-spatial task*, used 12 capital-letter, visually asymmetric consonants, half of which rhyme with /i/ (B,C,D,G,P,Z) and half of which don't (F,J,K,L,N,R) when the letter is *named*. Letters appeared either in their canonical orientation or in an upright mirror-reversed orien-

tation. Subjects had to make a forced-choice orientation judgment. Table 1C(a and b) lists the areas activated in the two separate contrasts, rhyme (letter-sound) *minus* letter-spatial and rhyme *minus* object.

As the authors point out, their results regarding phonological processing differ from those found by Zatorre et al. (1992) and Petersen et al. (1989). In particular, neither Broca's area nor temporoparietal cortex (specifically the supramarginal and angular gyri in the left hemisphere) turned up as significant foci in this study. The authors' interpretation of phonological processing centers on two observations. First, in both subtractions from the letter-sound condition three foci in prefrontal cortex showed significant activation: areas 11, 45, and 46 in the left hemisphere (see Table 3Ca, b). They argue that this result "suggests the recruitment of these areas for the programming of articulatory patterns for the generation of the actual sound of the letters" (Sergent et al., 1992, p. 76). Compare this claim to the claim articulated by Zatorre et al.: Zatorre et al. (1992) argue for a similar point—but for a slightly more posterior frontal area. In any case, it is noteworthy that neither experiment involved any (overt or covert) vocalization. The authors presumably believe that making a rhyme judgment requires the consultation of intended articulatory gestures, in which case the activations seen are a consequence of subjects consulting an articulatory representation to make a rhyme judgment based on articulatory representations.

The analysis of this study from the perspective of language research requires comments on two issues. First, visual letters are among the most abstract and artificial linguistic stimuli; they have an arbitrary relationship to the speech sounds of a language. Single letter names do not signify the sound of the letter because they are acquired words. So, *ell* is not the phonological representation of the liquid /l/, but merely its name or designation in an alphabetical arrangement. A letter's name (as opposed to its phonological and phonetic features) is, of course, an arbitrary lexical item; therefore it is not clear to what extent one is actually selecting phonological processing as opposed to *naming*. Importantly, all names are words. (Consider as an example of arbitrariness and "wordness" the British English *zed* compared to the American English *zee*.) Furthermore, notice that the names of several of the letters used in the study (B, C, P, G) are in fact homophonous with real words (bee, see, pee, gee). This, however, is precisely what the authors want to avoid. They point out in their introduction that the evidence indicates that all codes associated with a stimulus may be activated upon presentation (cf. the discussion of Petersen et al., 1989). With names and words, of course, the associated codes *may* be activated, including features like the grammatical category, lexical-semantic information, orthographic and word-shape information, and whatever else is associated with the stimulus. What the task thus constitutes is whether the end of a letter's name rhymes with /i/. While this level of analysis may seem nitpicky, the detailed analysis matters insofar as

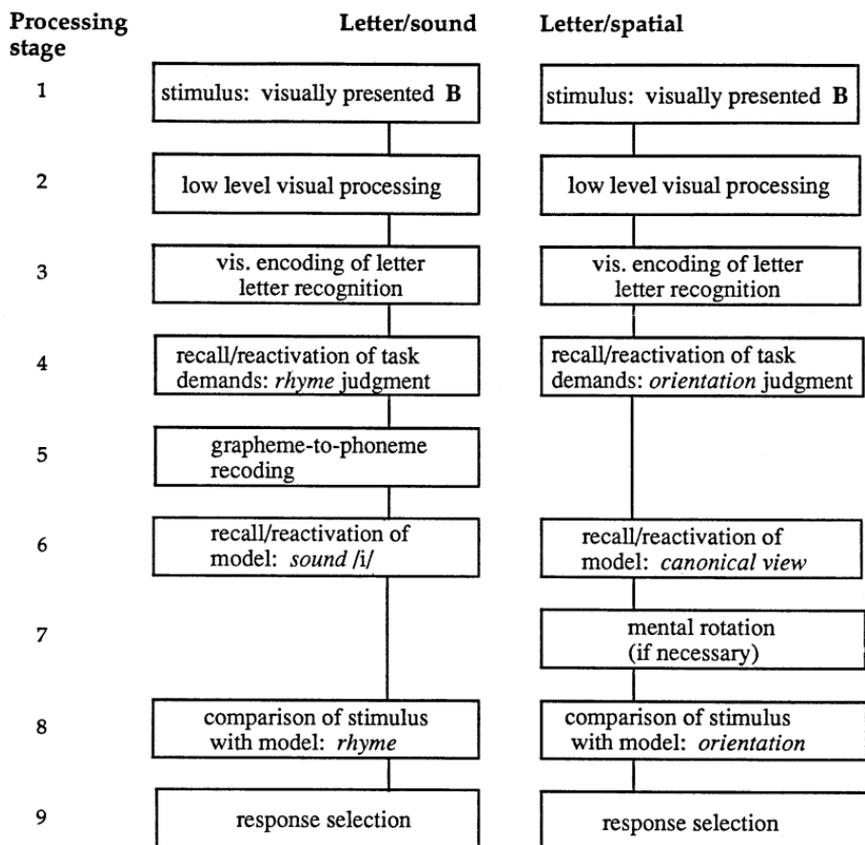
Experimental Task

FIG. 2. Task decomposition for Sergent et al. (1992). Schematized task decomposition for two conditions of the experiment in Sergent et al. (1992). In the letter/sound condition subjects had to judge whether a visually presented consonant rhymed with /i/. In the letter/spatial condition, subjects had to judge whether a visually presented consonant was in the canonical or mirror-reversed orientation. The letter/spatial condition acted as a control, and its PET scan image was subtracted from the letter/sound condition. For discussion, see text.

one tries to be explicit to what extent the *isolation* of some aspect of phonological processing was successful.

Second, the problem of task decomposition and the issue of matching test and control conditions within the paired-image subtraction paradigm can be illustrated very clearly using Sergent et al.'s study as an example. In order to appreciate the experimental design difficulties that face the investigators, consider Fig. 2.

Figure 2 reconstructs schematically the cognitive subroutines that are con-

tained in the execution of Sergent et al.'s experimental task. The stages shown are the minimal number of computations required to execute the tasks. Notice first that the two tasks, letter/sound (rhyme judgment) and letter/spatial (orientation judgment), are closely matched with respect to the number of computational components putatively required. Each task consists roughly of 8 stages; and with two exceptions (stages 5 and 7) the computations are similar—at least on the surface. In fact, stages 1 through 3 are probably identical. And even later stages are macroscopically similar in that they bring in to play similar cognitive processes (a memory component in stage 6 of both tasks, a decision component in stage 8 of both tasks, and response selection in stage 9 of both tasks).

This circumspect matching along number of computational components and general cognitive demands notwithstanding there remain a number of substantive differences between the two tasks. (Recall that the ideal subtraction occurs between two experimental tasks that are identical in all components except the one of interest.) Stages 1, 2, and 3 are likely to be identical. Also, both experimental tasks require that subjects remember what to do; this aspect of the two experimental tasks is likely to be similar in some respects (memory component) and different in others (different content of memory, distinct modalities required for task execution). Stage 5, grapheme-to-phoneme recoding, exists only in the letter/sound condition. One might argue that stage 7 is a corresponding operation for the letter/spatial task, and therefore the tasks are matched on this dimension. Notice, however, that mental rotation is an operation on the same mental representation whereas recoding is just that: a re-coding into a different representational format and therefore an instance of category switching. As such, these two components do not match as closely as one might initially suspect. Stage 6 requires that subjects recall the model that the current stimulus will be compared to. While there is a well-defined memory component, in one case the subject must reactivate the representation of a sound, in the other the subject must reactivate a visual representation. Stage 8, the comparison and decision stage, presumably differs between the two tasks given that the comparisons range over visual representations in one case and sound representations in the other. Summarizing, this analysis should persuade the reader that even in a study as carefully designed as Sergent et al.'s, one must be quite cautious about the interpretation. While it is possible to match experimental tasks very closely (and successfully), an explicit decomposition reveals that there may still exist substantive computational distinctions among the tasks that must constrain the interpretation of the subtraction PET results.

3.4 Demonet, Chollet, Ramsay, Cardebat, Nespoulos, Wise, Rascol, and Frackowiak (1992)

Demonet et al. (1992) investigated the “neural structures which mediate phonological, lexical and semantic processing of heard words” (p. 1753).

They “address[ed] directly whether there are separate areas dedicated to phonological and semantic processing of heard linguistic stimuli” (p. 1754). There were three experimental conditions in the study (see Tables 1D and 2D for details). (1) In a non-speech auditory control condition in which the stimuli were triplets of pure tones, the task was to respond to rising pitch in the third tone (e.g., 500 Hz–500 Hz–1000 Hz: yes response). (2) In a phoneme monitoring task in which the stimuli were multisyllabic nonwords, subjects had to monitor for a specific phoneme sequence (/b/ preceded by a /d/) occurring in a target stimulus. (3) A word task in which adjective-noun pairs were presented required subjects to categorize the noun phrases into arbitrarily determined groups. Targets were “positive” adjectives combined with nouns denoting animals smaller than a chicken or a cat, e.g., *kind mouse* would be a target, but *horrible horse* would count as a distractor.

The two language tasks were supposed to differ in that they were designed to tap phonological or semantic processing at the level of single words. The result relevant to phonological processing derived from the subtraction of the image generated during the tones task (acoustic control) from the image generated during the phoneme-monitoring task. The areas that showed rCBF increases for this comparison are listed in Table 3D. A regional increase in activation was seen in the superior, middle, and inferior temporal gyri in the left hemisphere and Broca’s area. Primary importance was attributed to the activation of regions in superior temporal cortex: The authors argue that the “neural structures associated with the phonological processes [. . .] include the associative auditory cortex in the left superior temporal gyrus and the anterior part of Wernicke’s area” (p. 1761). They also suggest a “[. . .] possible role of Broca’s area in phonological processing” (p. 1762).

From the point of view of task decomposition, one question concerns the actual execution of the phonemes task by subjects: As the task is described by Demonet et al., subjects monitored nonword strings for the phoneme /b/; in case they detected a /b/, they had to consult the entire sequence just presented to check if there was a /d/ somewhere preceding the /b/. If a /d/ was detected in the retrieved string, a positive response was generated. It may be that subjects actually performed the task this way. The summarized performance results suggest that the task was somewhat difficult for subjects, and one explanation of the difficulty is that subjects had to consult their memory representation of a recently presented string. There is, however, an alternative way to do the task, namely turning the order of the task around: Because the target is always a /d-/b/ sequence, monitor for /d/; if there is a /d/, continue monitoring; if you detect a /b/, respond YES. The structure of that phoneme monitoring task is perhaps easier, because it does not require the subject to reevaluate those parts of the string that are already past. If subjects are indeed performing the task as outlined in the original paper, then the task may be better characterized as a verbal short-term memory task, because a crucial component entails reevaluating a just-heard string

closely enough to detect a previously ignored target. In fact, the detection of targets in a multi syllabic non word sequence may be a hard task that actually requires subvocal rehearsal for adequate execution. Both strategies of performing the task may actually exist in the data, i.e., some subjects develop the latter strategy whereas some subjects perform the task as instructed.

Demonet, Price, Wise, & Frackowiak (1994a) designed a careful follow-up study to address precisely the points raised above. In the new experiment they were concerned (a) with distinguishing between the sequential and ambiguous components of the original task (which presented some problem with the interpretation) and (b) with elucidating the role of the frontal activation around Broca's area, in particular in view of the results of Paulesu et al. (1993; see below). Importantly, they replicated and extended the original findings. Specifically, they were able to show that if the phoneme-monitoring task contains a sequential component (e.g., /b/ after /d/) and an ambiguous component (e.g., stimuli and distractors use phonemes /b/ and /p/, making the target identification more difficult), subjects most likely resort to a verbal working memory strategy—hence the left frontal activation, which agrees with the results of Paulesu et al.'s study (1993) on verbal working memory. When these factors are unconfounded, the relative contributions of the sequential and ambiguous components generate differential results, and the frontal activation, attributed to the active engagement of verbal working memory, is attenuated, particularly when the ambiguity is eliminated.

Demonet, Price, Wise, & Frackowiak (1994b) have reanalyzed the original data using an improved analysis method (Woods, Cherry, & Mazziotta, 1992) and confirmed and sharpened the first results. The reanalysis shows, among other areas, activation in Broca's area and activation around the supramarginal gyrus (not seen in the first analysis). These sites were also activated in the follow-up study. Insofar as one interprets the difficult phoneme-monitoring task as requiring a verbal working memory component (e.g., rehearsal), the original results now also converge with Paulesu et al.'s (1993) study on working memory. Both Demonet et al. (1992, 1994a, 1994b) and Paulesu et al. (1993) attribute the rehearsal component of verbal working memory to a frontal region (Broca's area) and the phonological encoding/storage component to a cortical field around the supramarginal gyrus.

3.5 Paulesu, Frith, and Frackowiak (1993)

Paulesu et al. (1993) discuss the neural basis for the verbal component of working memory. The research is based on Baddeley's memory model (e.g., Baddeley, 1992). The experiment attempted to identify structures corresponding to specific components postulated within that framework, specifically the articulatory loop. By hypothesis, the articulatory loop consists of two processing components, subvocal rehearsal and phonological encoding.

The work is relevant to this review because an explicit claim is made about the neural correlates of phonological processing.

The study is summarized in Tables 1E and 2E. While the central motivation underlying the design is the fractionation of the articulatory loop into subvocal rehearsal and phonological encoding, a hypothesized bonus is that phonological processing is a cognitive process that comes for free in the design because phonological processing (in Baddeley's framework) is considered to be a combination of phonological encoding and rehearsal. Experiment 1 contrasted a verbal short-term memory task with a visual control task. The stimuli for the test condition were a sequence of six randomized, visually presented consonants that are phonologically dissimilar (the consonants used were not listed). Subjects were instructed to maintain the string in memory by rehearsing it subvocally. The control stimuli consisted of a set of unfamiliar (Korean) letters that subjects were instructed to remember (visual short-term memory task). The verbal task was designed to require phonological encoding *and* subvocal rehearsal. Experiment 2 was the familiar rhyme judgment task: Subjects had to make a rhyme judgment (target rhymes with /i/) on visually presented letters (cf. Sergent et al., 1992, who use the same experimental task). In this condition the control again consisted of visually presented unfamiliar (Korean) letters which had to be judged for visual similarity. The rhyming task was argued (on independent grounds) to require subvocal rehearsal *but not* phonological encoding. That allowed a separate comparison of the two language tasks; specifically, the comparison was designed to isolate phonological encoding, which is by hypothesis the only difference between the memory and rhyming conditions of the experiment.

The authors examined the "main effect of phonological processing by combining the results from the two experimental tasks and comparing them with the control tasks." How the two conditions were combined is not indicated in the paper. The results of the comparison, i.e., which areas show rCBF increase in both language tasks as compared to the two visual tasks, are summarized in Table 3E. Notice that with the exception of area 18 (an extrastriate visual area often also called V2) all activations in this study were bilateral.

Based on these activation results the authors state several claims: (1) The functional anatomy of the articulatory loop includes (bilaterally) Broca's area (Brodmann's area 44), superior temporal gyrus (BA 22–42), supramarginal gyrus (BA 40), and the insulae—in other words, most of the typical perisylvian language areas and their right hemisphere homologues. (2) Subvocal rehearsal is mediated by Broca's area in the left hemisphere. (3) Phonological encoding can be attributed to area 40 (supramarginal gyrus) of the left hemisphere. (4) The areas in superior temporal gyrus (BA 22/42) are "probably involved in phonological processing independent from memory [. . .]" (p. 344). Importantly, recent PET experiments by Smith and Jonides and their

colleagues (see Awh et al., 1994) converge in important ways with the result of Paulesu et al. (1993). Awh et al. (1994) designed tasks to selectively engage different components of working memory, and their results are consistent with Paulesu et al.'s claims with respect to verbal working memory. In particular, these investigators also attribute the rehearsal aspect of working memory to Broca's area and phonological encoding/short-term phonological storage to left posterior parietal cortex.

The analysis of this study in view of the other experiments discussed brings up one major issue. The nature of the precise contrast set up is unclear, for both the *memory* and the *rhyming* test conditions. Now, recall that an important experimental desideratum is a well-defined and minimal difference between test and control. In this experiment, the difference in task demands is substantive. Although both test and control have a strong memory component, the tasks are otherwise incomparable, because one is a language task whereas the other is a visual memory task—beyond short-term memory there is no overlap. Moreover, the relevant component of working memory is purportedly specifically linguistic in this model, so one would expect some other cerebral area to be mediating visual short-term memory. The question is, therefore: Is it plausible to compare tasks that are supposedly typical of language with tasks that are designed to be purely visual? Although the (subtracted) control conditions are well-matched to the test conditions with respect to extralinguistic performance factors, they are the *visual* analogue of a control that would perhaps better be anchored in language processing itself.³

4. THE NO-OVERLAP/SPARSE-OVERLAP RESULT

4.1 *No-Overlap/Sparse-Overlap across Studies*

To what extent are there consistent results across studies? We now turn to the comparison of the PET results across experiments. The five experiments were designed and executed with slightly different questions in mind. Paulesu et al. (1993), for instance, investigated verbal short-term memory, while Petersen et al. (1989) used their condition as an additional task embedded in a larger study of language processing. Demonet et al. (1992), in contrast, explicitly investigated phonological processing. There are, however, very important similarities across the studies as well (for explicit comparisons see Tables 1 and 2):

³ Paulesu et al., too, cite neuropsychological evidence that is consistent with their results. Note, however, that there is also directly contradictory neuropsychological evidence: Belleville et al. (1992), also working within the framework of Baddeley's working memory model, discuss lesion evidence that suggests exactly the opposite to the conclusion presented here. In particular, they suggest subvocal rehearsal is compromised by temporoparietal lesions.

- each report explicitly argues that a language component called *phonological processing* has been isolated;
- four of the five studies use rhyming tasks to isolate phonological processing;
- the stimuli are typically (4 out of 5 studies) pairs of items (CVC pairs, word pairs, individual letters compared to a target letter) that had to be compared along some predefined dimension;
- there are a number of similarities across studies concerning the conceptual decomposition of language; in particular, it is assumed that it is possible to *isolate* components of language processing like phonetics and/or phonology in the brain by using subtractive methodology.

Given the explicit claims of the reports and the similarities across studies it is reasonable to compare the results directly with one another. Ideally, one area or set of areas would always be implicated in phonological processing, because some underlying elementary computation required for phonological processing must be consistently activated if phonological processing is, in fact, invoked by the tasks. Are there one or more areas that show significant rCBF increase in all five studies? The answer, surprisingly, is that there is *no* single area or set of areas that is implicated in all PET studies of phonological processing. Let us call this the *no-overlap result*.

Table 3 lists the areas that show increased activation in the relevant comparisons. Across the 5 studies, 22 different areas show rCBF increase in response to the phonetic/phonological condition (not counting right-hemisphere activation sites). Eight cortical areas show significant rCBF increase in more than one study. Notice, however, that *not one single area shows significant activation across all five studies* and no common set of areas is active in 4 out of the 5 studies. Of the 8 areas that do show activation in more than one experiment, 3 are implicated in three out of five studies (these are discussed below) and 5 areas overlap in two experiments. With the exception of the results in Paulesu et al. (1993), all areas reported are in the left hemisphere.

The “maximal overlap” across studies occurs with the following three cortical areas that show increased activation in three of the studies. If we base our functional neuroanatomy of phonological processing on these five PET studies, these are the most likely candidates, and they are (from anterior to posterior in the brain):

- Broca’s area (approximately around Brodmann’s area 44)—activation seen by Zatorre et al. (1992), Demonet et al. (1992), and Paulesu et al. (1993);
- secondary auditory cortex (approximately around BA 42)—Sergent et al. (1992), Demonet et al. (1992), Paulesu et al. (1993);
- the supramarginal gyrus (approximately around BA 40)—Zatorre et al. (1992), Petersen et al. (1989), Paulesu et al. (1993).

Interestingly, each study is able to adduce favorable neuropsychological evidence (see papers for the references). Because there are five different PET results (and conclusions), this means that the authors were able to find deficit-lesion evidence supporting each distinct conclusion. This scenario is unsatisfactory insofar as it leaves one where one started out, namely with the neuropsychologically established result that (left hemisphere) perisylvian cortical areas are important to language processing including phonological processing. Consequently, although these first PET results confirm the relevance of the left perisylvian cortical areas for speech and language processing, they do not improve on the map of speech sound processing that has been established independently by cognitive neuropsychological research.

4.2 Which Area Mediates Which Process?

Of the three “candidate areas,” each one has a different function attributed to it. Broca’s area (BA 44) is implicated in phonological processing in three PET studies, but receives a decidedly different interpretation each time: For Zatorre et al. (1992) Broca’s area is central to the task of speech perception: “[W]hen a phonetic decision is required, there is a large focus in part of Broca’s area in the left hemisphere. . . . We propose that in making the phonetic judgment, subjects must access an articulatory representation involving neural circuits that include Broca’s area” (Zatorre et al., p. 848). Paulesu et al. (1993) find Broca’s area to be relevant to an entirely different component of processing. These authors suggest that their “results indicate that Broca’s area is crucial to the subvocal rehearsal system” (Paulesu et al., p. 344). The third group seeing area 44 activation (Demonet et al., 1992) makes no particular claim about Broca’s area. These investigators consider auditory cortex (BA 22/42) to be the critical neural substrate, and thus merely assert that there is a “possible role of Broca’s area in phonological processing” (Demonet et al., p. 1762). Similar discord obtains when comparing secondary auditory cortex (specifically, areas 22/42) and the supramarginal gyrus (specifically, area 40). Functions attributed to the supramarginal gyrus include phonological encoding (Petersen et al., 1989), phonological storage (Paulesu et al., 1993) and a (nonspecific) possible participation in phonetic/phonological processing (Zatorre et al., 1992). These different interpretations presumably constitute ordinary disagreement about the interpretation of experimental results. This fact, however, should not detract from the main point that there is no overlap to begin with.

Two situations obtain in the comparison among studies: Different experimental procedures generate overlapping results and very similar procedures generate nonoverlapping results. Consider first the case where there *is* overlap, for instance among the three studies that implicate area 40 (supramarginal gyrus). Although the three studies use rhyme judgments, they are otherwise quite different. One task requires judgments on visually presented word

pairs that appear at a rate of 48/min (Petersen et al., 1989), one on visually presented letters at a rate of 60/min (Paulesu et al., 1993), and one on auditorily presented non word strings at a rate of 14–18/min (Zatorre et al., 1992). That is, the three tasks are different in terms of task demands, sensory modality, and stimulus presentation rate but they all implicate area 40. This, in fact, may turn out to be the most robust result because three distinct experimental tasks supposedly tapping one module seem to consistently activate (among others) one specific area. One might interpret these three studies as successfully replicating each other with respect to the involvement of area 40 for some computation underlying the processing of speech sounds.

In contrast, consider the complementary (and more troublesome) comparison where there is almost no overlap, yet the tasks are extremely similar. Paulesu et al. (1993) use a rhyme judgment task just like Sergent et al. (1992): Both use visually presented letters that must be judged on whether they rhyme with /i/. The major difference between these two experiments lies in the rate of presentation (20/min versus 60/min). This difference (and possible other, even more subtle differences), then, must account for the fact that there is only *one* area (for only one of the subtractions reported in Sergent, namely the subtraction reported in Table 3Cb) that shows up significantly in both studies (area 42), although the studies are otherwise extremely similar. The region of overlap, area 42, is of course a very plausible candidate area to mediate some aspect of speech processing. Nevertheless, it is surprising that two experimental tasks that are so similar fail to converge more dramatically from the point of view of PET activations. This result could mean that differences in presentation rate lead to serious differences as reflected by PET results. A possible account for the disparity between the results is that at lower presentation rates, subjects' behavior is less constrained, leaving computational resources for the processing of representations irrelevant to those cognitive operations that were designed to be selectively tapped by the experimental task.

There is some overlap between the studies of Sergent et al. and Zatorre et al., namely area 24 (left anterior cingulate) and area 6 (left supplementary motor area). Because neither anterior cingulate nor SMA are typically associated with phonological processing or other language processes (these areas appear to be recruited for many different tasks across domains), it seems reasonable not to attribute special significance to their activations with regard to phonological processing.

4.3 Other Relevant Studies

To underscore how difficult it is to create a reliable functional neuroanatomy of phonological processing on the basis of functional neuroimaging studies, consider how the results compare to three other important language neuroimaging language studies.

In a recent functional magnetic resonance imaging (fMRI) study investigating language processing and hemispheric lateralization in men and women. Shaywitz, Shaywitz, Pugh, Constable, Skudlarski, Fullbright, Bronen, Fletcher, Shankweiler, Katz, and Gore (1995) used a nested design in a subtractive paradigm to isolate orthographic, phonological, and semantic processing. The test-control contrast set up to identify the neural loci of phonological processing was the following: In a control (orthographic) condition subjects had to judge the case alternation (upper versus lower case) in two visually presented consonant strings. In the test (phonological) condition subjects had to make a rhyme judgment on two visually presented nonwords. Interestingly, Shaywitz et al. found a difference in these results with respect to gender: The subtraction yielded bilateral activation in Broca's area for women subjects and relatively more left-lateralized Broca's area activation for male subjects. Although the phonological condition also generated activation foci in the superior and middle temporal gyri, the authors suggest that phonological processing is subserved by the inferior frontal gyrus (left Broca's area) in men and more bilaterally in the IFG in women. They did not find hemispheric differences in the orthographic or semantic conditions.

Another important study to consider used PET but was based on very different experimental intuitions. Recall that the studies we have considered all explore the language system using *single-word processing* tasks. A recent paper by Mazoyer, Dehaene, Tzourio, Frak, Murayama, Cohen, Levrier, Salamon, Syrota, and Mehler (1993) investigated the fractionation of the language system with PET using sentence-level stimuli (connected speech). These authors also had an interest in phonological processing and based on their findings argue for "a role for the left middle temporal gyrus in language-specific phonological analysis" (Mazoyer et al., p. 472). This result shows that sentence-level stimuli yield yet more different results from word-level stimuli in experiments attempting to selectively engage the phonological system. In any case, this study adds another cortical region to our list of candidate areas for the mediation of phonological computations.

A final experiment to consider is a PET study by Fiez, Tallal, Raichle, Miezin, Katz, and Petersen (1995). Fiez et al. presented subjects with tone pips, vowels, and CV or CVC syllables. In one condition, subjects listened passively; in another condition subjects were required to detect some target stimulus occurring among similar stimuli. The subtraction condition for both test conditions was a simple visual fixation task. Among the total set of activations, the authors report reliable foci of activation in response to the speech stimuli bilaterally in the superior temporal gyrus, bilaterally in the frontal opercular region, and in the SMA (midline). Fiez et al. attribute special importance to the left frontal opercular region, especially with respect to processing speech and its characteristic rapid temporal transitions.

Figure 3 schematizes the collected results. Figure 3 expands on Fig. 2 by considering the results from the left and right hemispheres and by including

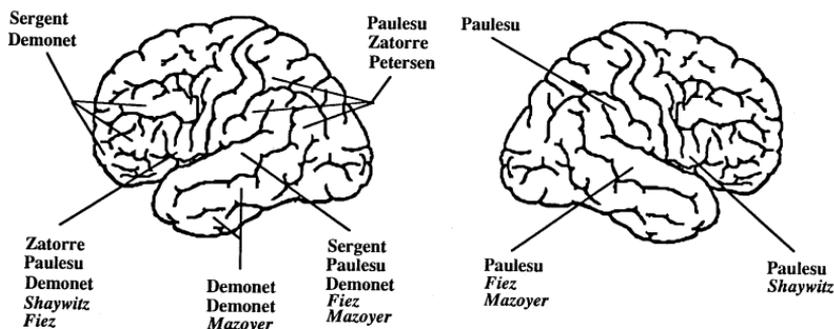


FIG. 3. Cortical areas implicated in phonological processing. Schematic summary of the results of the eight functional neuroimaging studies (seven PET studies, one fMRI study) discussed in the text. The author names point to areas to which special significance is attributed in the context of each study. The names in *italic* refer to the three studies discussed in section 4.3. Note that the implicated cerebral areas include prefrontal areas, the frontal operculum (bilateral), the superior temporal gyrus (bilateral), temporoparietal cortex (bilateral), and the middle and inferior temporal gyri.

the results from the three additional studies discussed in this section. Note that the inclusion of these three studies “consolidates” the sparse-overlap finding by bringing up more possible areas responsible for phonological processing.

4.4 *Who is Right?*

How can we interpret this state of affairs? Logically, there are at least three possibilities: (1) Everybody is right. All studies correctly identify at least one area that is crucial to some aspect of phonological processing. Phonological processing is, consequently, performed by a number of cortical regions, each of which mediates a particular elementary computation underlying phonological processing, namely that aspect necessary for the specific experimental task in question. However, because we have no information on what phonological or phonetic concepts are operative and relevant for each case, we cannot sharpen our understanding of how the brain processes and computes the sounds of language. (2) Nobody is right. No study is right, i.e., the area or areas actually underlying phonological processing have not been identified in any of the experiments. Although this is a logical possibility, it is somewhat unlikely given that essentially all (cortical perisylvian) language areas identified at one time or another have been implicated by PET studies in phonological processing. (3) Somebody is right. One of the experiments could be correctly identifying the network of areas that subserves phonological processing. However, there is no reason to prefer any one experiment over the others. Because the experiments are relying on underspecified and intuitive notions of language and phonological processing

and because no study makes explicit contact with any independent evidence pertaining to phonological processing, none of the interpretations is compelling. If any of the results and interpretations turn out to be correct, it is for coincidental reasons, and not because the experiment has effectively isolated some aspect of phonological processing based on independent evidence from cognitive psychology, psycholinguistics, or theoretical considerations.

5. DISCUSSION

Three factors account for the discrepancy among the PET results: (1) The decomposition of the experimental tasks is insufficiently specific: Precisely what cognitive processes are engaged typically remains unstated. Therefore it is difficult to compare test and control conditions and thus construct plausible interpretations of the subtraction results. (2) There is no specific cognitive–psychological, psycholinguistic, or theoretical motivation for the experiments. (3) When studying cognitive processes with PET, a special design—the paired-image subtraction—has been used. That design has a number of problems associated with it that become particularly salient with respect to language processing. Each of these problems is discussed in turn.

Insufficiently Explicit Experimental Task Decomposition

None of the studies provides an adequately detailed decomposition of the tasks used. As a consequence, it is not clear what computations go into a given task and what processes are subtracted out by the control task. Both the explicit contents of experimental tasks and the relationship between tasks and their respective controls remain poorly articulated. Each experimental condition, however, consists of a number of subroutines that must be performed in the execution of the experimental task. These unstated computational subroutines could account for important aspects of the results. The routines include nontrivial factors such as when a task is automatic versus controlled and attentionally modulated. Presumably, it is essential to know whether subjects can perform the task easily and automatically, freeing up resources for other, task-external computations or whether subjects' behavior is tightly constrained. For a graphical demonstration of this point, consider again Fig. 2, depicting two conditions from Sergent et al.'s (1992) study. This carefully constructed test-control pair still differs in *several* important ways (see the detailed discussion in section 3.3) that matter with respect to the interpretation of the results.

No Contact with Language Sciences

The experiments do not look to concepts beyond intuitive notions of phonological processing. There is no contact with any theoretical framework or model, and there is only sparse reference to any psycholinguistic work that

investigates speech or phonological processes. Consequently, from the perspective of psycholinguistics, the experiments proceed in a relatively unguided fashion. This is surprising insofar as there is a large literature on lexical and phonological theory and phonological processing. (For a detailed discussion of phonological theory, see Kenstowicz, 1994. For a number of articles reviewing aspects of sublexical and lexical processing from various perspectives see, for example, Marslen-Wilson, 1989, and Levelt, 1994. Detailed models of processing during perception are summarized in Klatt, 1989. Similarly, production models can be found in Levelt, 1989.)

The most straightforward interpretation of the no-overlap/sparse-overlap finding from the point of view of psycholinguistics is probably the one stated above as the first of three logical possibilities: All five studies are ‘‘correct’’ in the sense that they engage some region relevant to phonological processing. (In fact, since all the experiments use language stimuli, phonological processing is engaged in a trivial sense.) But it remains unacknowledged in these reports that phonological processing is not a unitary psychological operation but a highly complex set of subroutines (including *segmentation*, *syllabification*, *metrical analysis*, *prosodic analysis*), each of which may by itself engage a network of areas. A possible explanation of the no-overlap result, then, is that *different aspects of phonological processing* have been engaged. One could imagine that the different computations require access to distinct representations that are processed in different cortical or subcortical areas. A consequence of (i) a more detailed task analysis and (ii) contact with a model or theory of phonological processing would be that the experiments could connect with aspects of phonological processing about which we have independent evidence. In any case, from this perspective there exists a more charitable interpretation of the meta-analytic finding reported here: What looks like a failure to replicate is a consequence of the selective recruitment of distinct phonological subprocesses that have remained unarticulated.

Issues Specific to PET and the Subtractive Methodology

There are some systemic features of the PET methodology that might contribute to the no-overlap/sparse-overlap result. Even in the face of the hypothetical ideal psycholinguistic experiment that optimally isolates a processing component and perfectly controls for differences between test and control conditions (and hence allows for uncontroversial image subtraction and clear interpretation), there are principled limitations that contribute in systematic ways to the difficulty in doing PET studies of cognition.⁴

Some general differences in experimental task parameters may be suffi-

⁴ There are, naturally, principled technical limitations to the method that have been recognized for some time. For discussion of and references to a lot of the technical issues see, e.g., the Ciba Foundation volume on PET: Ciba Foundation Symposium 163, 1991; Roland, 1993; or Greitz, 1983.

cient to account for some of the variance. Raichle et al. (1994), for example, discuss an important finding that can have dramatic import for experimental design: Practicing and repeating an experimental task can affect the blood flow response over a few trials. One presumably has to control for that effect in a given test-control pairing by allowing for practice effects (or whatever response attenuation is relevant) to occur in both test and control conditions. Raichle et al. (1994) thus caution that small changes in stimulus parameters can lead to dramatic changes as seen in the CBF image. Raichle (1991) also mentions the possible effect of stimulus presentation rates. This is, in fact, a parameter along which the studies compared in this review differed. In particular, the stimulus presentation rate ranged from 14 items per min (Zatorre et al., 1992) to 60 items per min (Paulesu et al., 1993). If subtle stimulus timing differences in the face of otherwise identical experiments contribute significantly to the results, one can probably account for some aspects of the no-overlap result by appealing to different temporal properties of the experiments, even though they may isolate the same language computation.

Consider now the feature of the PET technology that is especially sensitive for experimenters. The temporal resolution of positron emission tomography is on the order of tens of sec. This constrains experimenters to present the stimuli of a given condition in blocks of the same type. This block-presentation of stimulus material and the sensitivity of the instrument in view of the signal-to-noise ratio make it helpful to use paired-image subtraction when investigating cognitive tasks (Fox et al., 1988). There are some problems associated with the method when studying language. (Some of the following points have been made in a very articulate way in the introduction to Sergent et al., 1992. I rely heavily on their exposition here. See also Demonet et al., 1993, and Raichle et al., 1994, for a similar discussion of the issues arising with the subtractive paradigm.) First, even if the putatively more "complex" cognitive computation is almost identical to the simpler, nested task, the difference may be a *qualitative* one. There is no a priori reason to believe that cognitive processes can be put in a subset relation and subtracted from one another, yielding a component subprocess. One assumption underlying the subtractive analysis is, therefore, that the tasks involved are processed in serially ordered, discrete stages. But that may not be true. In fact, for language processing this assumption is very likely false (McClelland and Rumelhart, 1981).

Second, possible feedback relations must apparently be excluded. This point is a corollary to the first one. Naturally, one could imagine a system of discrete stages that don't allow for feedback relations. The added components of a more complex task would then not feed back on prior components. But subtraction must have the built-in assumption of forward-only processing in order for the results to be quasi-interpretable. There exists, however, ample evidence (anatomical and experimental) that feedback is wide-

spread (Kandel et al., 1991; McClelland & Rumelhart, 1981; Altmann & Steedman, 1988; Trueswell, Tanenhaus, & Garsey, 1994).

Third, the experimental tasks implicitly presuppose that only the representations relevant to the task are activated. However, as Demonet et al. (1994b) also point out, ample experimental evidence indicates that subjects do in fact activate codes that are not explicitly tapped in a given experimental task (Tanenhaus, Flanigan, & Seidenberg, 1980; Rayner, Sereno, Lesch, & Pollatsek, 1995). Consequently, one must try to force subjects to attend selectively to particular stimulus attributes, but it is quite difficult to control for subjects attending only to the relevant stimulus dimension.⁵ Given that conditions must be presented in blocks, subjects may get better at the task and be able to process other, orthogonal computations, or they may employ strategies or heuristics that are different from the way they performed the task at the outset (cf. Raichle et al., 1994). It is virtually impossible to guarantee that subjects perform nothing but the cognitive computation in question. Therefore, it is rather difficult to interpret what the result of a subtraction represents in terms of cognitive processes. (For a general discussion of this issue in experimental psychology, see Sternberg's, 1969, discussion and extension of Donder's method.)

Brief Psycholinguistic Interlude

Consider as an example of this last problem what might plausibly occur when *non-word* stimuli are used to fractionate phonological processing from other linguistic computations. Non-word stimuli are used in the studies reviewed in various forms: as possible words (Demonet et al., 1992), as syllables (Zatorre et al., 1992), and as single letters (Sergent et al., 1992; Paulesu et al., 1993). There is an advantage to using these kinds of stimuli in that they do not *overtly* require semantic or grammatical linguistic representations. It is not obvious beyond argument, though, why the processing of these stimuli isolates a computational component of the language system. In fact, one might wonder whether it is coherent at all to attempt to isolate a linguistic computation. The presupposition of the studies is that non-word tasks are effective at tapping phonological processes (relative to some control baseline). Consider, however that an experimental task using non-word stimuli engages not just phonological processes but also generates *at least* (i) a search through the lexicon to find the item, (ii) a morphological analysis of

⁵ Note, however, that there are grounds for optimism: There are experiments that demonstrate convincingly that within-modality selective attention can lead to important differences in PET scan results. Corbetta et al. (1990) have shown, for example, that attention to particular stimulus parameters like stimulus color, shape, or velocity of visual stimuli engages specific and different cortical fields. Of course, whether this kind of selective engagement holds for language processing remains to be shown.

the item, and (iii) a comparison to the closest neighbors in the lexicon (i.e., items that are very similar) insofar as the item is not listed itself. Regardless of the particular processes that actually occur, it may be the case that a non-word task bootstraps the subject into other language-specific computational subroutines and that it is just not possible to *isolate* a language processing component in a straightforward manner.

Suppose, for example, that the computational system that yields linguistic representations is a dedicated and automatic cognitive system, and that when you encounter a linguistic stimulus, the language apparatus is *automatically* engaged (Fodor, 1983). That is, all computational modules relevant to language processing are engaged. In such a system one could not isolate any single component performing independently. There are evidently ways to sample from particular subroutines or modules more than others, perhaps by selectively enhancing certain representations through an attentional system. Consider, for instance, that very broken (ungrammatical, elliptical) speech is often interpretable. Similarly, there are Jabberwocky-like sentences and conceptually impossible sentences that allow for syntactic analysis but are otherwise totally uninterpretable. However, even insofar as these kind of stimuli can access the representations of a specific module of the system more than others (at least phenomenologically), that fact neither implies nor requires that the other processing subroutines are silent or disengaged. Rather, it may be the case that even those computational processes not directly invoked by an experimental task are activated if the stimulus is linguistic. What processing subroutines are engaged are probably *modulated* by what type of linguistic information is available, by attentional requirements, by memory limitations, or by other internal system states. Importantly, one could imagine a plausible conceptual framework that questions on principled grounds whether one can isolate particular components of the language system. Since there are no a priori reasons to rule out either viewpoint, the alternatives must be motivated. And given the state of the art, considerable argument will be required.

A final issue concerns one of the assumptions implicit in this research. The studies characteristically reflect a commitment to localizing specific functions to specific areas of the brain. This is a natural consequence of the method, but one wonders to what extent this framework will extend our understanding of the functional organization of the brain. In fact, PET studies are in this sense conceptually equivalent to the deficit-lesion approach. PET studies obviously have a number of advantages, the most important one being able to look at intact brains *in vivo*. But given the brain level of analysis and the logic underlying the experimentation, any explanations will be very similar to the neuropsychological explorations of the same questions. There is, of course, nothing wrong with trying to make contact with the results gained through cognitive neuropsychology. But arguably one goal is to extend and clarify the results from cognitive neuropsychology. It is our charge

to find ways to give PET a chance to demonstrate why it is a real departure from and advance over previous methods. There are at least two ways in which this research can go in qualitatively new directions. First, one challenge is whether cognitive psychologists and psycholinguists are able to develop experimental tasks that address relevant questions while being “temporally tolerant” or “temporally resistant.” That is, one needs tasks that can be executed for the required amount of time (say tens of secs) but about which one can be confident that the desired cognitive process is in fact engaged. Because the entire research program is predicated on the assumption that one can effectively isolate a process, this challenge has to be met in order to proceed in a satisfactory manner. Second, the systematic application of PET studies to language processing will allow one to go beyond the idea of a one-to-one correspondence between language function and brain area. It is becoming increasingly likely that the various subroutines of language are processed not by single cerebral areas but by an array of areas distributed throughout the brain. One will want to identify the areas and then consider the spatio-temporal activation patterns of the array of language areas that have been reliably identified.

6. CONCLUSION

The successful use of PET across studies of the same cognitive computation demands some degree of overlap among the areas that are attributed to the cognitive computation allegedly invoked. A comparison of PET studies of phonological processing shows that this *overlap-criterion* is only marginally satisfied. The analysis yields the following conclusions:

1. In a comparison of five PET experiments on phonological processing that were very similar in their task demands, no overlap in results was found in local increases in rCBF across experiments. We are therefore not yet in a position reliably to attribute phonological processes (or the computations underlying the construction of the representations) to a specific region of the brain.

2. All the studies reviewed were able to adduce deficit-lesion correlation evidence consistent with the presented PET findings and interpretations. Five phonological studies yielded five findings and these in turn were consistent with five different pieces of evidence from the deficit-lesion correlation literature.

3. There are principled questions about PET (systemic issues) that have not been completely resolved so as to allow for straightforward application of the method to cognitive psychological problems. These issues include the difficulties due to the subtraction paradigm.

4. When studying the cerebral organization and representation of language, we should consider what we know independently about language from other scientific disciplines. There is ample psycholinguistic research to

guide the experiments and there are a number of well-articulated models and theories. A consequence of the lack of contact with the results of cognitive psychology, psycholinguistics, and linguistic theory is that the tasks do not map onto linguistic representations in any obvious way. Future work will require investigators to be increasingly, sensitive to the results of other disciplines concerned with language in order to converge on satisfying interpretations.

Although the PET studies of language do not yet converge to the extent one hopes for, the studies have generated two provocative new strands of results. First, the results suggest that a serious reevaluation of the "canonical" functional neuroanatomy of language (see, e.g., Geschwind, 1970) is in order. Whereas Wernicke's area, the angular gyrus, the arcuate fasciculus, and Broca's area continue to be consistently implicated in language processing, the PET results implicate a number of additional areas and therefore dramatically extend the range of where in the brain one will have to look when studying language. Second, a number of the PET studies implicate Broca's area in the processing of verbal working memory. This is true explicitly of the studies of Paulesu et al. (1993; see also Awh et al., 1994), and the results of other studies are consistent with this interpretation. Specifically, the experimental tasks used by Demonet et al. (1992) and Zatorre et al. (1992) both have a clear verbal working memory component, and one can thus begin to work with the hypothesis that Broca's area plays a crucial role in verbal working memory (for additional research broadly consistent with this idea see Stromswold, Alpert, Rausch, & Caplan, 1996; Dronkers, Shapiro, Redfern, & Knight, 1992).

The goal of this critical assessment is naturally not to disparage a new method that will contribute to our understanding of functional neuroanatomy (especially used in conjunction with some of the other new imaging methods like functional magnetic resonance imaging and magnetoencephalography). Rather, the goal is to sensitize the reader of functional neuroimaging research to the fact that there is still room for critical distance and skepticism regarding the method and its implementation, and that the results to date are problematic. What we cannot yet infer from PET studies of language, for example, is which areas mediate phonological processes. To be sure, that is a negative result, since creating a map is what we set out to do. But cartographic achievement requires analytical care as well as the machinery necessary to chart the frontier. This kind of cognitive neuroscience cannot be done without the best cognitive psychology, psycholinguistics, and linguistics. PET studies of cognitive processes cannot be viewed as a shortcut that circumvents the prerequisite analytical work.

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