

Hemispheric Dissociation in Access to the Human Semantic System

Guillaume Thierry,^{1,*} Anne-Lise Giraud,²
and Cathy Price^{3,*}

¹School of Psychology
University of Wales
Bangor
United Kingdom

²Cognitive Neurology Unit
Johann Wolfgang Goethe University
Frankfurt am Main
Germany

³Wellcome Department of Imaging Neuroscience
Institute of Neurology
London
United Kingdom

Summary

Patient studies suggest that speech and environmental sounds are differentially processed by the left and right hemispheres. Here, using functional imaging in normal subjects, we compared semantic processing of spoken words to equivalent processing of environmental sounds, after controlling for low-level perceptual differences. Words enhanced activation in left anterior and posterior superior temporal regions, while environmental sounds enhanced activation in a right posterior superior temporal region. This left/right dissociation was unchanged by different attentional/working memory contexts, but it was specific to tasks requiring semantic analysis. While semantic processing involves widely distributed networks in both hemispheres, our results support the hypothesis of a dual access route specific for verbal and nonverbal material, respectively.

Introduction

Clinical neuropsychology was established in the 1860s following the observation that lesions to the left inferior prefrontal cortex disrupt the motor programming of speech (Broca, 1861). Later, lesions to the left posterior superior temporal gyrus were shown to disrupt the identification of the “auditory images of speech” (Wernicke, 1874), and the first neurofunctional model of language processing emerged in the form of a left temporal-frontal network (Lichtheim, 1885). Numerous patient studies have confirmed a left hemispheric dominance for spoken language processing, and others have shown functional specialization in the right temporal lobe for nonverbal, high-level cognitive processes, e.g., music (Griffiths et al., 1997; McFarland and Fortin, 1982), prosody (Ross, 1981; Ross et al., 1997), and the emotional content of speech (Heilman and Gilmore, 1998; Pell, 1999).

Although spoken language impairments often corre-

late with deficits in environmental sound recognition (e.g., Clarke et al., 2000; Pinard et al., 2002), speech-specific auditory comprehension deficits have been described. The corresponding syndrome, known as pure word deafness, is a rare clinical profile classically induced by bilateral temporal lesions (Auerbach et al., 1982; Coslett et al., 1984; Di Giovanni et al., 1992; Tanaka et al., 1987; Yaqub et al., 1988). However, pure word deafness has also been reported following focal temporal lesions in the left hemisphere only (Auerbach et al., 1982; Metz-Lutz and Dahl, 1984; Saffran et al., 1976; Seliger et al., 1991) or subcortical lesions extending into the temporal and parietal white matter of the left hemisphere (Takahashi et al., 1992).

Auditory agnosia without aphasia refers to the reverse dissociation, i.e., auditory impairment restricted to environmental sounds. Although rare, three references to such cases following right hemisphere lesions can be found in the literature: (1) one stroke patient with extensive lesions encompassing right frontal, temporal, and parietal regions (Spreen et al., 1965); (2) one stroke patient with a focal right posterior superior temporal lesion (Fujii et al., 1990); and (3) one patient with bilateral lesions in the putamen who displayed auditory agnosia without aphasia only after the right lesion (Taniwaki et al., 2000).

Functional dissociations in processing or accessing the meaning of verbal and nonverbal information therefore appear to support a left/right anatomical dissociation. Only one case of auditory agnosia without aphasia has been reported following a lesion confined to the left hemisphere (patient SD of Clarke et al. [2000]), and pure word deafness following lesions confined to the right hemisphere is also extremely rare (Roberts et al., 1987). These exceptional cases may conceivably be related to abnormal lateralization.

In contrast to neuropsychological studies of patients, neuroimaging studies of normal subjects have failed to reveal a left/right functional dissociation for verbal and nonverbal comprehension. Although a clear left-greater-than-right asymmetry is often observed for processing spoken language compared to rest or nonverbal control conditions (Binder et al., 1997; Démonet et al., 1992, 1994; Giraud and Price, 2001; Humphries et al., 2001; Nishizawa et al., 1982; Price et al., 1996; Scott et al., 2000; Thierry et al., 1998), auditory words activate both left and right temporoparietal areas, even when nonlinguistic acoustic processes are controlled for (Belin et al., 2000; Binder et al., 1997, 2000; Démonet et al., 1992, 1994; Giraud and Price, 2001; Hickok and Poeppel, 2000; Humphries et al., 2001; Mummery et al., 1999; Price et al., 1996; Scott et al., 2000; Thierry et al., 1998, 1999).

Similarly, environmental sounds activate bilateral temporal areas relative to rest (Engelen et al., 1995; Humphries et al., 2001) and relative to noise bursts matched for duration and amplitude (Giraud and Price, 2001). Direct comparison between listening to spoken words and listening to environmental sounds (Giraud and Price, 2001; Humphries et al., 2001) have shown increased left temporal activation for words but have

*Correspondence: g.thierry@bangor.ac.uk (G.T.), c.price@fil.ion.ucl.ac.uk (C.P.)

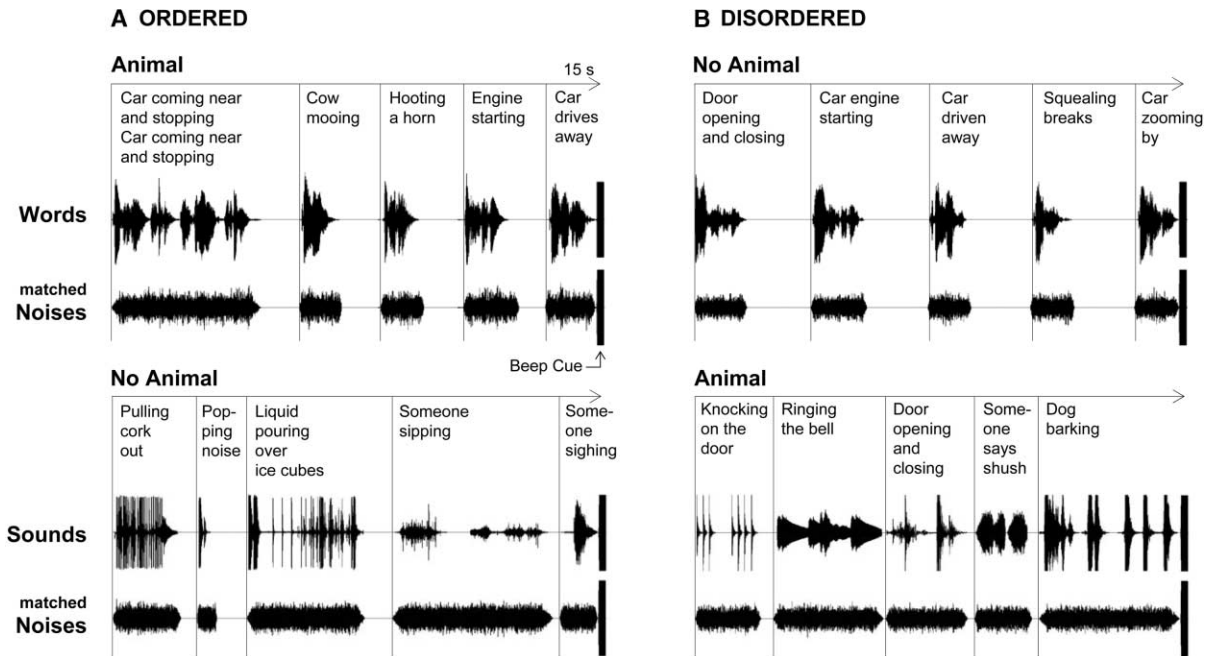


Figure 1. Examples of Meaningful Auditory Sequences and Matched Baselines

Four examples of sequences made of words (Words) or environmental sounds (Sounds) used in the semantic tasks together with matched scrambled Words/Sounds sequences used in the baseline task (matched Noises). Half of the series contained a reference to an animal (Animal) and the other half did not (No Animal).

(A) Half of the series was logically ordered.

(B) The other half of the series was disordered.

not found significant right temporal activation for environmental sounds. However, verbal and nonverbal stimuli have not yet been compared during tasks requiring explicit semantic analysis equated for both types of stimuli. Engaging the participants in parallel tasks may be necessary to insure the full comparability of verbal and nonverbal comprehension.

In this study, we sought to (1) control for global acoustic differences between verbal (spoken words) and nonverbal (environmental sounds) sources (such as average frequency and amplitude), (2) match words and environmental sounds in meaning, and (3) engage subjects in semantic tasks that were equivalent for words and environmental sounds. To test whether any differences obtained across stimuli could be due to differences in attentional/short-memory requirements, we used two semantic tasks of different difficulty: an easy *categorization* task and a difficult *sequence* interpretation task (Figure 1). For the categorization task, participants were asked to deal with the stimuli one-by-one and indicate whether a reference to an animal was present or not in the auditory sequence by making button presses (animal/no animal) after hearing a beep cue. For the sequence interpretation task, subjects were explicitly required to put stimuli in relation to one another within a series and decide whether the corresponding events could be considered as logically ordered or not. Finally, baseline conditions for both *words* and *sounds* were included to control for most low-level acoustic differences in the perceptual processing of the two sources. In each baseline, digitally scrambled environmental sounds or words were presented and subjects made a

button press on hearing the beep at the end of each sequence. Therefore, in this experiment, both low-level perceptual processes and high-level semantic analysis were controlled. Consequently, the contrasts between words and sounds were expected to reveal an intermediary stage in the processing of meaning interfacing between low-level acoustic processing and high-level semantic analysis. In the light of neuropsychological cases, we expected to observe a left/right dissociation in superior temporal activations, posterior and/or anterior to the areas involved in low-level acoustic processing.

Results and Discussion

Participants' behavioral data recorded during scanning indicated that performance on words and sounds were identical (Figure 2): there was no difference in reaction times (RTs) or hits between words and sounds in either task. As expected, the sequence task was the most difficult (equally for words and sounds) although it was not impossible (responses were significantly above chance). The categorization task was easier than sequence interpretation, and the *baseline* task was the easiest. On the basis of these behavioral results, we can be confident that differences between stimulus types are not due to differences in task difficulty. Furthermore, the sequence task, which required holding semantic attributes of different items in working memory and processing every single stimulus in a sequence before a decision could be made, was more demanding in terms of attentional resources and short-term memory.

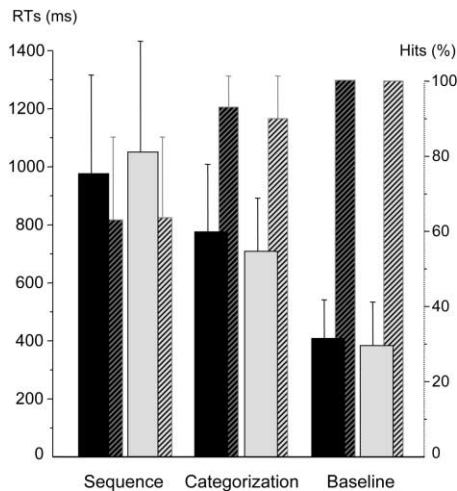


Figure 2. Behavioral Results

Mean subject response times in millisecond (RTs, plain bars) and hit rates in percent (Hits, hashed bars) in the sequence interpretation (left), categorization (middle), and baseline (right) task. Black bars indicate results for sounds and gray bars depict results for words. There was no difference between stimulus conditions whatever the task, either in terms of reaction times (RTs) [$F(1,11) = 0.003$; $p = 0.954$] or in terms of accuracy [$F(1,11) = 0.071$; $p = 0.795$]. Moreover, there was no type \times task interaction for either hits [$F(1,11) = 0.136$; $p = 0.719$] or RTs [$F(1,11) = 1.067$; $p = 0.2107$], showing that performances for words and sounds were comparable in each task taken separately. Sequence interpretation was a more difficult task than categorization. Hit rates were significantly higher [$F(1,11) = 48.52$; $p < 0.0001$] in categorization (mean = $91.3\% \pm 10\%$) than in sequence interpretation ($63.5\% \pm 21\%$) and accordingly RTs were shorter [$F(1,11) = 11.06$; $p < 0.007$] in categorization (738 ± 211 ms) than in sequence interpretation (1004 ± 355 ms). Finally, the baseline task displayed ceiling effects with 100% hits and shortest RTs (396 ± 138 ms). Following a pilot study (data not shown), 16 sequences of words and sounds for which behavioral performances were similar between sources were retained from a set of 30 and used in the neuroimaging experiment.

The functional imaging analysis identified areas that were:

- More active for words (W) than sounds (S) after low-level perceptual processes had been controlled with the baseline conditions (Bw and Bs). The corresponding contrast was $[(W - Bw) > (S - Bs)]$.
- More active for sounds than words after low-level perceptual processes had been controlled $[(S - Bs) > (W - Bw)]$.
- Commonly activated by sounds (S) relative to baseline (Bs) and words (W) relative to baseline (Bw). These areas were identified by the conjunction of $[(W - Bw)$ and $(S - Bs)]$. Conjunction analysis identifies areas where the t value for each of two or more contrasts exceeds “the minimal t value.”

We also investigated the task by stimulus interaction to determine how the above effects were modulated by task difficulty.

We found (Table 1; Figure 3A) that words relative to sounds increased activation in left anterior and posterior superior temporal areas and sounds relative to words increased activation in the right posterior superior tem-

poral cortex. There was no interaction with task in any of these areas ($Z < 2.0$) and no other effects specific to words or sounds that occurred in one task context only. In other words, none of the effects were modulated by task difficulty. Thus, we demonstrate a dissociation in hemispheric activation for words and sounds in the temporal lobe that has been suggested previously by neuropsychological studies of patients with temporal lobe damage (Fujii et al., 1990; Spreen et al., 1965).

In addition, the conjunction of words and sounds, relative to the noise baselines, activated ventral and dorsal regions of the left posterior inferior frontal cortex, bilateral cerebellum, and central regions of the right superior temporal cortex, with extensive activation throughout both anterior and posterior regions of the left superior and middle temporal cortex. Again, there were no interactions with task in any of these areas.

Remarkably, the only difference between our functional imaging results and those that have previously compared words and environmental sounds (Giraud and Price, 2001; Humphries et al., 2001) was the sound-specific activation in the right posterior temporal cortex. This, of course, is critical for demonstrating the double dissociation. Humphries et al. (2001) also note that right posterior superior temporal activation was enhanced when subjects listened passively to sequences of environmental sounds that corresponded to spoken sentences, but they did not discuss the effect because it did not reach significance and because low-level acoustic differences between environmental sounds and words were not controlled. Overall, therefore, it appears that sound-specific effects in the right posterior temporal cortex were (1) most significant when subjects made semantic decisions (this study); (2) observed only at a nonsignificant level in the study by Humphries et al. (2001) when subjects listened passively to sequences of sounds that corresponded to spoken sentences; and (3) not observed at all by Giraud and Price (2001) when subjects simply listened to or named individual sounds.

To investigate the differences between studies, we directly compared the data from the present study with those reported by Giraud and Price (2001), which were collected using the same scanner, processed following the same procedure, and which also included stimulus-specific noise baselines. There were 12 different subjects in each study, which allowed us to use second level (random effect) analyses based on the subject-specific contrasts for each sound or word condition relative to the corresponding noise baseline. When contrasted with naming and repeating (Giraud and Price, 2001), semantic analysis equated for words and sounds elicited significantly more activation in the right posterior superior temporal cortex for sounds (Table 2; Figure 3B). In addition, semantic decisions increased activation in left temporal and ventral frontal regions for both words and sounds and in the left cerebellum for words only.

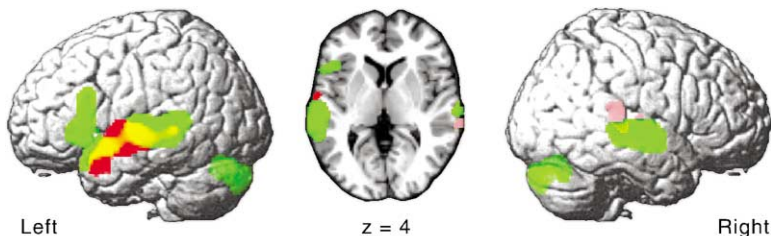
Figure 4 shows the effect sizes in the right posterior temporal area for (1) listening to sounds, (2) naming sounds, (3) categorization on sounds, (4) sequence interpretation on sounds; and the corresponding effects with words. The advantage for sounds was present for both semantic categorization and sequence interpretation but absent (and in the opposite direction) for listening and naming. This observation is not consistent with the

Table 1. Semantic Decisions on Words and Sounds (Over Task)

	BA	Coordinates (mm)			Z Scores	Simple Main Effects	
		x	y	z		W > Bw	S > Bs
(A) Words and Sounds [(W - Bw) + (S - Bs)]							
L. middle/superior temporal	21/22	-60	-48	6	5.2	5.9	3.6
	21/22	-58	-22	0	>8.0	>8.0	6.2
	38	-58	8	-10	5.9	>8.0	3.8
	38	-50	20	-24	4.9	6.0	3.1
R. middle/superior temporal	21	68	-36	0	5.2	3.8	4.0
	21	64	-14	0	>8.0	7.3	5.9
	21	64	0	-8	5.2	6.0	4.0
L. inferior frontal	47/45	-46	20	2	6.1	4.5	4.0
	45/44	-52	18	12	5.7	4.0	3.9
R. cerebellum		16	-86	-30	6.1	4.6	4.1
		40	-68	-28	4.9	3.3	3.4
L. cerebellum		-4	-76	-24	6	4.3	3.9
(B) Words > Sounds [(W - Bw) > (S - Bs)]							
L. middle/superior temporal	21	-60	-40	0	5.2	7.6	5.2
	21	-64	-6	-2	>8.0	>8.0	3.0
		-44	6	-20	4.8	5.0	NS
	38	-48	12	-22	6.1	6.4	2.1
(C) Sounds > Words [(S - Bs) > (W - Bw)]							
R. superior temporal	42/22	70	-30	12	4.6	NS	4.8
	42	62	-16	8	4.6	2.7	4.9

Location, Brodmann's area (BA), coordinates according to Talarach and Tournoux (1988), and Z scores for activations for semantic decisions relative to baseline decisions. (A) Common for words (W) and sounds (S); (B) for words more than sounds; (C) for sounds more than words. In addition, right hand columns show Z scores for the simple main effects of words (W) relative to the word baselines (Bw) and sounds (S) relative to the sound baseline (Bs); NS, not significant ($p > 0.08$, uncorrected).

A CONTROLLED SEMANTICS



B COMPARISON WITH LISTENING AND NAMING

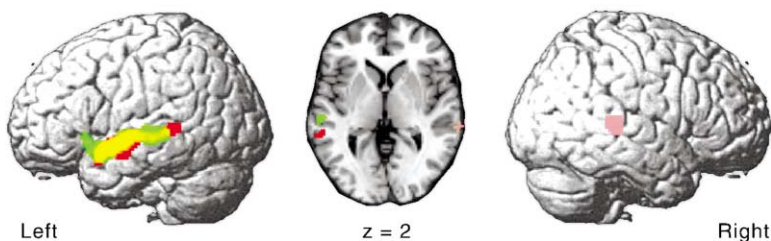


Figure 3. Neuroimaging Results Superimposed on High-Resolution MRI

(A) SPM renderings of brain activations in the main semantic experiment: green areas are those activated for words and sounds. Red areas are those more active for words than sounds each being controlled by their respective baseline. Yellow areas are overlap of green and red effects. Pink areas are those more active for sounds than words each being controlled by their respective baseline. Activations threshold was $p < 0.08$ corrected for multiple comparisons. Details of activations are shown in Table 1.

(B) Random effect contrasts between the present study and passive listening/naming sounds or repeating words in a previous study using similar stimuli (Giraud and Price, 2001). Colored areas indicate regions that were more active in the present study than in the Giraud and Price (2001) study. Color coding and statistical threshold are identical to (A). Details of activations are shown in Table 2.

Table 2. Greater Activation for Semantic Study Relative to Listening and Naming

	BA	Coordinates (mm)			Z Scores	Simple Main Effects	
		x	y	z		SEM	L/N
(A) Words and Sounds							
L. middle/superior temporal	21/22	-70	-34	0	4.9	>8.0	1.9
	21/22	-58	-24	0	5.4	>8.0	4.0
	38	-58	6	-10	6.4	5.6	2.6
	38	-60	10	-18	4.6	5.0	1.5
L. inferior frontal	47/45	-50	18	-4	6.3	6.0	1.9
L. cerebellum		-6	-76	-22	4.5	6.0	1.7
(B) Words Only							
L. cerebellum		-8	-82	-34	5.2	4.9	2.1
(C) Sounds Only							
R. superior temporal	42/22	70	-34	6	5.9	5.5	NS

Random effects comparison of the semantic study (SEM) and the listening and naming study (L/N) by Giraud and Price (2001): (A) for words and sounds relative to noise baselines; (B) for words relative to baseline; (C) for sounds relative to baseline. Coordinates are from Talairach and Tournoux (1988). Right hand columns show the simple main effects for each study; NS, not significant ($p > 0.08$, uncorrected).

effect arising at the level of perceptual analysis because, if this was the case, we would have expected a corresponding effect for listening and naming. Indeed, the right superior temporal areas we found activated for semantic analysis of sounds lies dorsal to the right superior temporal areas that Zatorre and collaborators (Zatorre and Belin, 2001; Zatorre et al., 2002) associate with perceptual processing of music (i.e., superior spectral resolution in the right superior transverse sulcus as compared to superior temporal resolution in the left auditory cortex). Furthermore, as the sound advantage was comparable in both categorization and sequence interpretation, the right superior temporal activation does not appear to be due to variations in attentional demands or demands on short term memory which were higher during sequence interpretation than categorization (see above). The advantage for sounds in the right posterior

superior temporal cortex therefore appears to be specific to semantic analysis.

The difference between the present study and previous results obtained by Giraud and Price (2001) are most likely to be due to the different semantic requirements of the tasks used. While semantic processing is involved for naming sounds as well as for semantic categorization/sequence interpretation, sound naming only requires access to a single semantic concept, whereas the semantic decision tasks require additional semantic information and analysis. For example, when deciding whether a sound refers to an animal, one might access the concept (e.g., cow), compare the cow concept to the concept of an animal, and decide if they are congruent. Interestingly, one can argue that categorization (this is an animal) is achievable without retrieving the exact source of the sound (this is a cow), but the four animal sounds used in the experiment were highly recognizable (cow, dog, cockerel, and mosquito) and strongly primed by the target category. In the sequence interpretation task, on the other hand, it is necessary to access the semantic concept associated with each sound and, in addition, access the semantic representation (e.g., drinking champagne) that is indicated by the whole sound series (sometimes referred to as compositional semantics). Previous imaging studies have demonstrated that left anterior temporal areas are activated during semantic analysis (Mummery et al., 1998; Vandenberghe et al., 1996), but not during naming (Martin et al., 1996).

Our results indicate that, in addition to the distributed semantic system that is common to sounds and words, there are left hemisphere areas that are more involved in semantic processing triggered by verbal stimuli and right hemisphere areas that are more involved in semantic analysis elicited by environmental sounds. However, because the effects were not modulated by task difficulty, the exact level of processing at which we observe a verbal/nonverbal dissociation must correspond to an early stage in semantic processing that is intermediate between acoustic processing and semantic analysis and which characterizes a differential access route to semantic memory. More specifically, we propose that, since acoustic processing of environmental sounds is

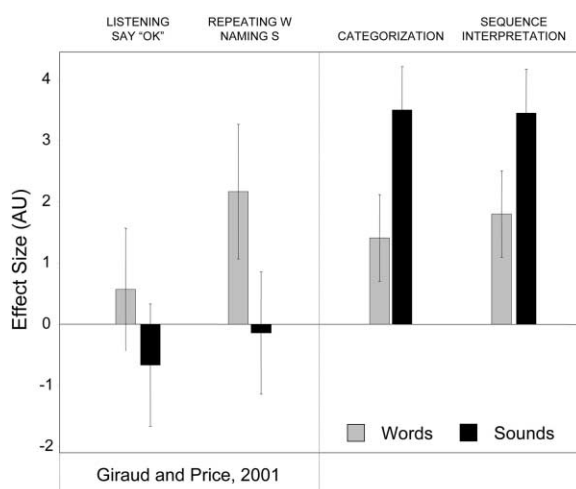


Figure 4. Effect Sizes of Activation in the Right Posterior Superior Temporal Cortex at Voxel (70, -34, 6) Obtained for the Different Tasks

Effect size for words (gray) and sounds (black) for listening/saying "OK" and repeating words/naming sounds (Giraud and Price, 2001) and for categorization and sequence interpretation (this study). Error bars depict standard errors.

likely to be more reliant on right ventral superior temporal activation than words (Zatorre et al., 2002), the connectivity to the left lateralized semantic network is primarily right sided for sounds and left sided for words.

A functional dissociation in the access routes to semantic memory on the basis of verbal versus nonverbal stimuli is compatible with the dual coding theory (see for instance Paivio, 1991) which attributes the classical reaction time advantage of concrete relative to abstract noun processing to a right hemisphere mental imagery system (Jessen et al., 2000; Kounios and Holcomb, 1994). By this account, concrete nouns yield faster recognition times because both symbolic representations and mental imagery are available, whereas only the former can be accessed for abstract nouns. In the same vein, it has been proposed that there are hemispheric differences in the type of information—categorical or associative—that can be used to achieve semantic processing, with perceptual information being mainly available to the right hemisphere and conceptual information being available to both hemispheres (see for instance Hines et al., 1984; Shibahara and Lucero-Wagoner, 2001). Together, these theories of cerebral functional asymmetries point to a particular efficiency of the right hemisphere in dealing with the semantic analysis of environmental sounds relative to verbally coded information. The present comparison of words and sounds allows us to look directly into this functional dichotomy because both are auditory stimuli and their overall semantic content has been closely matched.

General Conclusions

By combining data from two studies, we demonstrate that the left anterior and posterior temporal areas were more active for words than sounds irrespective of task difficulty; and the right posterior superior temporal cortex was specifically activated by semantic analysis of environmental sounds. We have therefore demonstrated a neurofunctional dissociation between the left and the right hemispheres that operates during semantic processing of verbal and nonverbal auditory material in normal participants.

The absence of any interaction with the task difficulty indicates that the dissociation was reliable in different attentional/memory contexts and could not be accounted for by differences in acoustic differences between words and sounds (Figure 4).

In addition to the previously reported left/right functional asymmetry relating to low-level perceptual differences in the response of the auditory cortex to spoken language and music/pure tone processing (Zatorre et al., 2002), our findings suggest the existence of a left/right asymmetry relating to semantic access triggered by verbal or nonverbal material, respectively. While this intermediary stage is predominantly left lateralized for verbal comprehension in normal right-handed participants, an alternative right posterior superior temporal route appears to be available for meaningful nonverbal auditory stimuli. Further experiments will be needed to determine differences in the connectivity between left and right auditory cortices on the one hand and the left hemisphere semantic system on the other.

Experimental Procedures

Subjects

Twelve, healthy, right-handed volunteers (mean age 24.2 ± 6.3 years old) gave written consent to participate in 12 positron emission tomography (PET) scans (Siemens CTI III camera) involving intravenous injection of water labeled with ^{15}O . The dose received was 9 mCi per measurement, and the study was approved by the local hospital ethics committee and the UK Administration of Radioactive Substances Advisory Committee (ARSAC).

Design

There were 12 scans involving four activation conditions and two baseline conditions (noises), each repeated twice, with order counterbalanced over subjects. Activation conditions conformed to a fully balanced 2×2 design with two types of auditory stimuli and two types of task.

Stimuli

The activation stimuli were sequences of either words (referred to as W) or sounds (referred to as S) with each sequence lasting 15 s and ending with a distinctive beep. Word series were the closest possible translation of sound series. A total of 16 different sequences (4 per scan) were presented for both words and sounds. Words and sounds were identical across tasks, but the order of a sequence was never repeated. Fifty percent of sequences included a stimulus that referred to an animal and fifty percent were logically ordered (Figure 1). The baseline stimuli were sequences of "Noises" corresponding to the words or sounds presented in the activation conditions. These noises were produced by scrambling each word and sound sequence using a MatLab procedure that kept the average output frequency, and the frequency range equal to that of the source stimuli. The noise sequences were created to match the sequences of word and sound series, respectively. We refer to the word baselines as Bw and the sound baselines as Bs.

Tasks

The activation task was either categorization (does one of the stimuli in the sequence refer to an animal?) or sequence interpretation (is the sequence of stimuli logically ordered?).

For the categorization task, participants were asked to deal with the stimuli one-by-one and indicate whether a reference to an animal was present or not in the auditory sequence by making button presses (animal/no animal) after hearing the beep cue. For the sequence interpretation task, subjects were explicitly required to put stimuli in relation to one another within a series and decide whether the temporal succession of corresponding events could be considered as ordered or not. For the baseline task, subjects made a button press on hearing the beep at the end of the sequence.

In all conditions, participants were instructed to respond as quickly and accurately as possible with a button press after hearing the beep cue. Finger responses were alternated within subjects across blocks and behavioral data were recorded on-line (Figure 2).

Data Analysis

Realignment, normalization, and statistics were performed with SPM99 (www.fil.ion.ucl.ac.uk/spm) (Friston et al., 1995, 1996). Images were spatially smoothed with a 16 mm Gaussian filter. The linear contrasts compared (1) each activation condition to its specific baseline (i.e., $W - Bw$ and $S - Bs$); (2) the differences between $W - Bw$ and $S - Bs$ (Table 1; Figure 3A); (3) the differences between categorization and sequence interpretation for each stimulus type separately; and (4) the interaction between task and stimulus type. Conjunction analyses were then used to identify common activations for $W - Bw$ and $S - Bs$, common effects of stimulus type over task (e.g., $W - Bw > S - Bs$), and common effects of task over stimulus type. This is equivalent to the conventional analysis of a factorial design.

Comparison with Data from Giraud and Price

There were 12 subjects in the Giraud and Price (2001) study. As in the semantic analysis study described above, subjects listened to blocks of (1) environmental sounds; (2) heard words corresponding

to the source of those sounds; and (3) baseline conditions for individual words and sounds (Bw and Bs) generated by shaping broadband white noises with the low-pass temporal envelope of each meaningful stimuli. In contrast to the semantic analysis study, subjects in the Giraud and Price study were instructed to respond to each stimulus individually (the presentation rate was one stimulus per 4 s). Six subjects said "OK" in response to each stimulus irrespective of condition; the other six subjects named the source of the environmental sound (e.g., "dog" for hearing the sound of a dog barking), repeated back the heard words, and said "OK" to each of the baseline stimuli.

Random effect statistical comparisons (based on between subject variance only) were used to compare the effect sizes in the two studies. The effects of interest, computed separately for each study, over task, were: (1) words and sounds > Bw and Bs; (2) words - Bw; (3) sounds - Bs (Table 2; Figure 3B). In addition, we report the effect sizes for words and sounds relative to baselines, for each task separately, in the right posterior superior temporal area, which was more active for semantic analysis of sounds than words (Figure 4).

Acknowledgments

The authors wish to thank Nick Ellis, Mark Roberts, Marilyn Vihman, and Uta Noppeney for their assistance and comments.

Received: July 11, 2002

Revised: March 3, 2003

Accepted: March 18, 2003

Published: May 7, 2003

References

- Auerbach, S.H., Allard, T., Naeser, M., Alexander, M.P., and Albert, M.L. (1982). Pure word deafness. Analysis of a case with bilateral lesions and a defect at the prephonemic level. *Brain* 105, 271-300.
- Belin, P., Zatorre, R.J., Lafaille, P., Ahad, P., and Pike, B. (2000). Voice-selective areas in human auditory cortex. *Nature* 403, 309-312.
- Binder, J.R., Frost, J.A., Hammeke, T.A., Cox, R.W., Rao, S.M., and Prieto, T. (1997). Human brain language areas identified by functional magnetic resonance imaging. *J. Neurosci.* 17, 353-362.
- Binder, J.R., Frost, J.A., Hammeke, T.A., Bellgowan, P.S., Springer, J.A., Kaufman, J.N., and Possing, E.T. (2000). Human temporal lobe activation by speech and nonspeech sounds. *Cereb. Cortex* 10, 512-528.
- Broca, P. (1861). Perte de la parole, ramollissement chronique et destruction partielle du lobe antérieur gauche du cerveau. *Bull. Soc. Anthropol. Paris* 2, 235-238.
- Clarke, S., Bellmann, A., Meuli, R.A., Assal, G., and Steck, A.J. (2000). Auditory agnosia and auditory spatial deficits following left hemispheric lesions: evidence for distinct processing pathways. *Neuropsychologia* 38, 797-807.
- Coslett, H.B., Brashear, H.R., and Heilman, K.M. (1984). Pure word deafness after bilateral primary auditory cortex infarcts. *Neurology* 34, 347-352.
- Démonet, J.F., Chollet, F., Ramsay, S., Cardebat, D., Nespoulous, J.L., Wise, R., Rascol, A., and Frackowiak, R. (1992). The anatomy of phonological and semantic processing in normal subjects. *Brain* 115, 1753-1768.
- Démonet, J.F., Price, C., Wise, R., and Frackowiak, R.S. (1994). Differential activation of right and left posterior sylvian regions by semantic and phonological tasks: a positron-emission tomography study in normal human subjects. *Neurosci. Lett.* 182, 25-28.
- Di Giovanni, M., D'Alessandro, G., Baldini, S., Cantalupi, D., and Bottacchi, E. (1992). Clinical and neuroradiological findings in a case of pure word deafness. *Ital. J. Neurol. Sci.* 13, 507-510.
- Engelen, A., Silbersweig, D., Stern, E., Huber, W., Doring, W., Frith, C., and Frackowiak, R.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.
- Friston, K.J., Holmes, A., Worsley, K.J., Poline, J.-B., Frith, C.D., and Frackowiak, R.S.J. (1995). Statistical parametric maps in functional imaging: a general linear approach. *Hum. Brain Mapp.* 2, 189-210.
- Friston, K.J., Ashburner, J., Poline, J.-B., Frith, C.D., Heather, J.D., and Frackowiak, R.S.J. (1996). Spatial realignment and normalization of images. *Hum. Brain Mapp.* 2, 165-189.
- Fujii, T., Fukatsu, R., Watabe, S., Ohnuma, A., Teramura, K., Kimura, I., Saso, S., and Kogure, K. (1990). Auditory sound agnosia without aphasia following a right temporal lobe lesion. *Cortex* 26, 263-268.
- Giraud, A.L., and Price, C.J. (2001). The constraints functional neuroimaging places on classical models of auditory word processing. *J. Cogn. Neurosci.* 13, 754-765.
- Griffiths, T.D., Rees, A., Witton, C., Cross, P.M., Shakir, R.A., and Green, G.G. (1997). Spatial and temporal auditory processing deficits following right hemisphere infarction. A psychophysical study. *Brain* 120, 785-794.
- Heilman, K.M., and Gilmore, R.L. (1998). Cortical influences in emotion. *J. Clin. Neurophysiol.* 15, 409-423.
- Hickok, G., and Poeppel, D. (2000). Towards a functional neuroanatomy of speech perception. *Trends Cogn. Sci.* 4, 131-138.
- Hines, D., Sawyer, P.K., Dura, J., Gilchrist, J., and Czerwinski, M. (1984). Hemispheric asymmetry in use of semantic category information. *Neuropsychologia* 22, 427-433.
- Humphries, C., Willard, K., Buchsbaum, B., and Hickok, G. (2001). Role of anterior temporal cortex in auditory sentence comprehension: an fMRI study. *Neuroreport* 12, 1749-1752.
- Jessen, F., Heun, R., Erb, M., Granath, D.O., Klose, U., Papassotiropoulos, A., and Grodd, W. (2000). The concreteness effect: evidence for dual coding and context availability. *Brain Lang.* 74, 103-112.
- Kounios, J., and Holcomb, P.J. (1994). Concreteness effects in semantic processing: ERP evidence supporting dual-coding theory. *J. Exp. Psychol. Learn. Mem. Cogn.* 20, 804-823.
- Lichtheim, L. (1885). On Aphasia. *Brain* 7, 433-484.
- Martin, A., Wiggs, C.L., Ungerleider, L.G., and Haxby, J.V. (1996). Neural correlates of category-specific knowledge. *Nature* 379, 649-652.
- McFarland, H.R., and Fortin, D. (1982). Amusia due to right temporoparietal infarct. *Arch. Neurol.* 39, 725-727.
- Metz-Lutz, M.N., and Dahl, E. (1984). Analysis of word comprehension in a case of pure word deafness. *Brain Lang.* 23, 13-25.
- Mummery, C.J., Patterson, K., Hodges, J.R., and Price, C.J. (1998). Functional neuroanatomy of the semantic system: divisible by what? *J. Cogn. Neurosci.* 10, 766-777.
- Mummery, C.J., Ashburner, J., Scott, S.K., and Wise, R.J. (1999). Functional neuroimaging of speech perception in six normal and two aphasic subjects. *J. Acoust. Soc. Am.* 106, 449-457.
- Nishizawa, Y., Olsen, T.S., Larsen, B., and Lassen, N.A. (1982). Left-right cortical asymmetries of regional cerebral blood flow during listening to words. *J. Neurophysiol.* 48, 458-466.
- Paivio, A. (1991). Dual coding theory: retrospect and current status. *Can. J. Psychol.* 45, 255-287.
- Pell, M.D. (1999). The temporal organization of affective and non-affective speech in patients with right-hemisphere infarcts. *Cortex* 35, 455-477.
- Pinard, M., Chertkow, H., Black, S., and Peretz, I. (2002). A case study of pure word deafness: modularity in auditory processing? *Neurocase* 8, 40-55.
- Price, C.J., Wise, R.J., Warburton, E.A., Moore, C.J., Howard, D., Patterson, K., Frackowiak, R.S., and Friston, K.J. (1996). Hearing and saying. The functional neuro-anatomy of auditory word processing. *Brain* 119, 919-931.
- Roberts, M., Sandercock, P., and Ghadiali, E. (1987). Pure word deafness and unilateral right temporoparietal lesions: a case report. *J. Neurol. Neurosurg. Psychiatry* 50, 1708-1709.
- Ross, E.D. (1981). The aprosodias. Functional-anatomic organization of the affective components of language in the right hemisphere. *Arch. Neurol.* 38, 561-569.
- Ross, E.D., Thompson, R.D., and Yenkosky, J. (1997). Lateralization

of affective prosody in brain and the callosal integration of hemispheric language functions. *Brain Lang.* 56, 27–54.

Saffran, E.M., Marin, O.S., and Yeni-Komshian, G.H. (1976). An analysis of speech perception in word deafness. *Brain Lang.* 3, 209–228.

Scott, S.K., Blank, C.C., Rosen, S., and Wise, R.J. (2000). Identification of a pathway for intelligible speech in the left temporal lobe. *Brain* 123, 2400–2406.

Seliger, G.M., Lefever, F., Lukas, R., Chen, J., Schwartz, S., Codeghini, L., and Abrams, G. (1991). Word deafness in head injury: implications for coma assessment and rehabilitation. *Brain Inj.* 5, 53–56.

Shibahara, N., and Lucero-Wagoner, B. (2001). Access to perceptual and conceptual information in the left and right hemispheres. *Percept. Mot. Skills* 93, 649–659.

Spree, O., Benton, A.L., and Fincham, R.W. (1965). Auditory agnosia without aphasia. *Arch. Neurol.* 13, 84–92.

Takahashi, N., Kawamura, M., Shinotou, H., Hirayama, K., Kaga, K., and Shindo, M. (1992). Pure word deafness due to left hemisphere damage. *Cortex* 28, 295–303.

Talairach, J., and Tournoux, P. (1988). *Co-Planar Stereotaxic Atlas of the Human Brain. 3-Dimensional Proportional System: An Approach to Cerebral Imaging*, New York: Thieme Medical Publishers, Inc. Edition (Stuttgart: George Thieme Verlag).

Tanaka, Y., Yamadori, A., and Mori, E. (1987). Pure word deafness following bilateral lesions. A psychophysical analysis. *Brain* 110, 381–403.

Taniwaki, T., Tagawa, K., Sato, F., and Iino, K. (2000). Auditory agnosia restricted to environmental sounds following cortical deafness and generalized auditory agnosia. *Clin. Neurol. Neurosurg.* 102, 156–162.

Thierry, G., Doyon, B., and Demonet, J.F. (1998). ERP mapping in phonological and lexical semantic monitoring tasks: a study complementing previous PET results. *Neuroimage* 8, 391–408.

Thierry, G., Boulanouar, K., Kherif, F., Ranjeva, J.P., and Demonet, J.F. (1999). Temporal sorting of neural components underlying phonological processing. *Neuroreport* 10, 2599–2603.

Vandenberghe, R., Price, C., Wise, R., Josephs, O., and Frackowiak, R.S. (1996). Functional anatomy of a common semantic system for words and pictures. *Nature* 383, 254–256.

Wernicke, C. (1874). *Der Aphasische Symptomencomplex* (Breslau, Cohn & Weigert).

Yaqub, B.A., Gascon, G.G., Al-Nosha, M., and Whitaker, H. (1988). Pure word deafness (acquired verbal auditory agnosia) in an Arabic speaking patient. *Brain* 111, 457–466.

Zatorre, R.J., and Belin, P. (2001). Spectral and temporal processing in human auditory cortex. *Cereb. Cortex* 11, 946–953.

Zatorre, R.J., Belin, P., and Penhune, V.B. (2002). Structure and function of auditory cortex: music and speech. *Trends Cogn. Sci.* 6, 37–46.