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Dissociations Within the Anterior Attentional System: Effects of Task Complexity and Irrelevant Information on Reaction Time Speed and Accuracy

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Patients with focal frontal or nonfrontal lesions were compared with control participants on 4 reaction time (RT) tasks varying in levels of complexity based on a feature-integration model of detection. Superior medial lesions affected simple RT speed. Increasing the demands of feature detection did not differentially affect speed of correct responses among the groups. Frontal structures appear to play little role in correct integration of features during detection. The analysis of error types within the complex task revealed a frontal lobe hemispheric distinction between sensitivity and bias: right dorsolateral—decreased sensitivity; left dorsolateral—altered response bias. The frontal lobes, particularly right dorsolateral, were required to inhibit an incorrect response. There are at least 3 functionally and anatomically separable anterior attentional processes.

Despite almost 50 years of investigation of the effects of brain damage on reaction time (RT), firm conclusions remain elusive. Although many reports have claimed to find slowed simple RT after brain damage (Benton & Joynt, 1959; Blackburn & Benton, 1955; Bub, Audet, & Lecours, 1990; Dee & Van Allen, 1973; Elsass & Hartelius, 1985; Godefroy, Cabaret, & Rousseaux, 1994), the effects have not been very large. Even when task complexity has revealed significant impairment after brain damage, some individuals within that defined group have always performed normally (Benton & Blackburn, 1957; Blackburn & Benton, 1955; Dee & Van Allen, 1971; Howes & Boller, 1975; Tartaglione, Oneto, Manzino, & Favale, 1987). There has also been a modest trend over many studies that right-brain damage causes more RT slowing than left-brain damage, but again, the effect has not been consistently significant. Differential effects of posterior and frontal lesions are more conclusive. Parieto–occipital regions are critical for many preattentive perceptual discriminations and for attention-dependent feature conjunction operations.

Effects found of frontal lesions on RT, particularly complex RT tasks, have been quite variable, perhaps because of the remarkable inconsistency in experimental tests used and in lesion type and location. Medial frontal lesions have been associated with deficits in various complex RT tasks (Drewe, 1975; Leimkuhler & Mesulam, 1985; Luria, 1973). Right lateral frontal regions have been implicated in sustained attention (Pardo, Fox, & Raichle, 1991; Rueckert & Grafman, 1996; Wilkins, Shallice, & McCarthy, 1987). Left lateral frontal lesions have been related to impaired divided attention (Godefroy & Rousseaux, 1996b). Lesions in a wide variety of frontal regions have been implicated in excessive sensitivity to interference: orbital (Fuster, 1997; Stuss & Benson, 1986; Whyte, Fleming, Polansky, Cavallucci, & Coslett, 1998), right lateral (Stuss et al., 1999), and bilateral superior medial (Richer & Lepage, 1996). Largely on the basis of inference from known anatomical connectivity, the anterior cingulate gyrus (ACG) has been linked to attentional functions (Mesulam, 1981). Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) activation studies in normal subjects have suggested several possible roles for the ACG: response selection from a set of competing stimuli (Pardo, Pardo, Janer, & Raichle, 1990; Paus, Petrides, Evans, & Meyer, 1993; Posner & Petersen, 1990) and monitoring and regulation of conflicting responses (Botvinick, Nystrom, Fissell, Carter, & Cohen, 1999).

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We report the results of a series of RT tests in a large group of patients with well-defined focal lesions restricted to frontal or nonfrontal (NF) regions. The tasks were designed to allow serial analyses of RTs and errors for a simple RT task and for progressively more complex tasks as well as analysis of the roles of increasing distraction and of redundant information. Detection using feature integration was the theoretical framework selected to assess the effects of increasing complexity. The higher level of task included the mental operations of the previous task plus added processes (Donders, 1969; Sternberg, 1969).

The patient groups were analyzed by regional localization within the frontal lobes. We anticipated that deficits in target selection would be seen with right frontal lesions and that all frontal groups would show sensitivity to increased distraction.

Method

Subjects

Thirty-six patients with focal lesions and 12 nonpatient control participants, matched as closely as possible to the patients for age, sex, education, and handedness, were recruited for the study. The patients were divided into groups on the basis of their lesion location (see below). The brain pathology had to be a single focal lesion confined to the frontal lobes, including dorsolateral subcortical lesions involving deep frontal white matter and dorsal caudate (for a rationale, see Stuss et al., 1994), or in NF brain regions. A minor overlap of frontal and NF (less than 10%) structures or a minor secondary lesion was observed in 2 patients. The etiology had to be an acquired acute disorder, such as infarction, hemorrhage, trauma, or resection of a benign tumor. Patients, with particular attention to trauma patients, were selected only if there was no evidence of diffuse brain pathology. Controlling for the time since injury also minimized the potential confound of the presence of more diffuse pathology with certain etiologies. The varied etiologies allowed for the assessment of potential localization differences within the frontal lobes (Stuss, Shallice, Alexander, & Picton, 1995). In addition, several studies have demonstrated that the localization of the lesion is more relevant than the etiology (Burgess & Shallice, 1996; Elsass & Hartelius, 1985; Stuss et al., 1994).

All lesions were localized with standard atlases, and their profiles were circumscribed onto templates according to the method of Damasio and Damasio (1989). Lesion size was quantified by superimposing the lesion contour for each axial slice on a constant pixel diagram and counting the number of pixels within the lesion area. A percentage of total brain area damaged was obtained by dividing the lesion count by the total pixel count for all axial slices. Other inclusion and exclusion criteria for the patients were post onset at least 1.3 months (all but one past 2.5 months; $M = 42$ months; range =1.3–291 months) and absence of severe aphasia, no clinically detectable neglect, and no other significant neurological or psychiatric disorders.

We studied 25 patients with lesions confined to the frontal lobes and 11 patients with NF lesions, divided into the following anatomical classifications on the basis of our previous research (Stuss, Bisschop, et al., 2001; Stuss et al., 1998; Stuss, Floden, et al., 2001; Stuss, Levine, et al., 2000): left dorsolateral frontal (LDL; $n = 6$), right dorsolateral frontal (RDL; $n = 7$), inferior medial (IM; $n = 6$), superior medial (SM; $n = 6$; subjects in this group may have had extension into IM areas; see Stuss et al., 1998), and NF ($n = 11$). The lesions for each patient in this standard anatomical classification schema are depicted in Figure 1. In a small number of cases (4 left NF patients), scans had been available for lesion documentation but were lost prior to depiction and quantification. Descriptions of the patients' etiology, lesion size, chronicity (months post onset), lesion location, and handedness, divided according to the above anatomical classification, are presented in Table 1.

All subjects reported normal color vision, and none had difficulty distinguishing the colors used in the test. To provide a measure of general intellectual ability, the National Adult Reading Test—Revised (NART–R) was administered. Summary statistics for the demographic data are presented in Table 2.

Experimental Procedure and Apparatus

Four different types of RT tasks were administered (see also Stuss et al., 1989; see Figure 2). For each, the objective was to detect a target stimulus and press a handheld response button with the dominant hand as quickly as possible, making as few errors as possible. In some of the tasks, a nontarget stimulus was presented, requiring a response using a second button mechanism held in the nondominant hand. All subjects were able to perform the task, and the different tasks provided an approach for analyzing any effect of differences over and above simple motor response speed.

Stimuli were presented on a computer monitor, with a screen measuring approximately 35 cm × 35 cm, located approximately 1 m from the subjects' head position. The basic stimulus for each task, presented in the center of the screen, was one of four shapes: circle, square, triangle, or cross. The shapes were light gray or colored on a dark gray background. The approximate size of each shape was 3 cm × 3 cm. Once the test began, the stimuli were presented at interstimulus intervals varying between 4 s and 6 s. The stimulus stayed on the screen for 2 s or until a response was made.

The four RT tasks were presented in a fixed order. In the *simple* detection RT (simple RT) task, one shape, selected in a random manner for each subject from four alternatives (circle, square, triangle, cross), was presented repetitively for 50 trials, preceded by 5 practice trials. The simple RT task was repeated again at the end of the session to provide an assessment of fatigue and an indirect index of motivation. The goal of the simple RT task was to react to the presence of a visual stimulus as quickly as possible by depressing a response button held in the dominant hand.

The other three RT tasks—*easy*, *complex*, and *redundant*—were stimulus discrimination tasks based on feature identification and conjunction of different degrees of difficulty. In each of these discrimination RT tasks, there were 100 trials, preceded by 10 (15 in the complex task) practice trials. The target appeared randomly on about 25% of the 100 trials in the easy, complex, and redundant discrimination RT tasks. In the one-feature detection easy discrimination RT task, all four shapes were presented in random order. One of the shapes was identified before the beginning of the task as the target (dominant hand response), all other shapes being nontargets (nondominant hand responses).

In the three-feature detection complex discrimination RT task, all four shapes were again presented. This time, however, each of the shapes could be in one of the following colors: red, green, yellow, or blue. Moreover, each shape, regardless of the color, could vary in the presence of different internal line orientations: horizontal, vertical, backward slanting, or forward slanting. Each stimulus varied in the combination of shape, color, and internal line texture. The target was defined as a particular combination of the three features: a specific shape, in a specific color, with a specific internal line texture (e.g., a red circle with backward-slanting lines). The subject had to pay attention to all three characteristics to visually identify and respond to the correct target

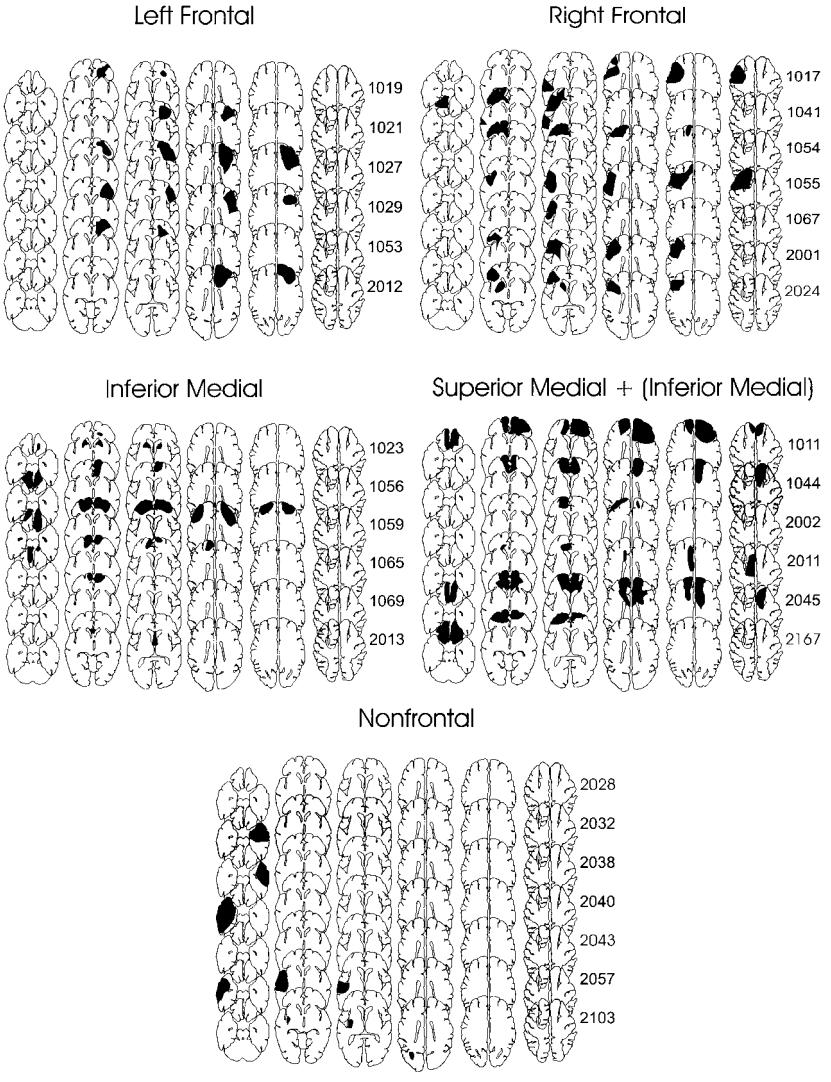

Figure 1. Lesion location of each subject within the five patient groups: left dorsolateral frontal, right dorsolateral frontal, inferior medial, superior medial, and nonfrontal.

stimulus. The stimuli had a 25% probability of sharing all three features (targets), a 32% probability of sharing two of the target's three features (e.g., a blue circle with backward-slanting lines), a 32% chance of sharing one feature (e.g., a blue circle with horizontal lines), and an 11% chance of sharing no features with the targets (e.g., a blue cross with horizontal lines). Varying the number of features the nontargets shared with the target permitted an analysis of the effect of the different number of nontarget shared features on speed of RT and error rate.

The one-feature detection redundant discrimination RT task was similar to the complex task with one exception. The difference between the redundant and complex RT tasks was such that in the former, each of the three features defining the target was unique to the target. None of the nontarget stimuli shared any features (color, shape, or internal line texture) with the target stimulus. If the target were a red circle with horizontal lines, no other stimulus would be red, be a circle, or have internal horizontal lines. Thus, the target in the redundant task could be defined by one feature, the others being "redundant." Because one feature could define the target, this condition was equivalent in difficulty to the easy RT task, and the RTs should have been equivalent, unless the subject was distracted by the extra features. Although the subject was informed that there were no shared features between the target and nontarget, no hint was given as to what strategy might be used to complete the task.

Dependent Measures and Statistical Analyses

RT analyses. The analyses were designed primarily to test the following concepts: (a) basic detection and speed of motor response—analysis of simple RT task performance; (b) fatigue—proportional change in RT between the second and first simple RT tasks; (c) one-step processing complexity—proportional change between the easy (one-feature target detection) and simple (basic detection) tasks; (d) complexity of three-feature versus one-feature discrimination—proportional change between the complex and easy tasks; (e) effect of irrelevant information on speed of one-feature target detection—proportional change between the redundant and easy tasks (in essence, both tasks are identical, in that the discrimination and response could be made on the basis of one

Table 1
Etiology, Lesion Location, Lesion Size, Time Since Injury (TSI), and Handedness (Hand) Within Patient Groups

Subject	Etiology	Lesion location	Lesion size (%)	TSI (months)	Hand
		Left dorsolateral frontal			
1019	Trauma	DL, ACG, IM, polar	0.87	31.1	R
1021	Hemorrhage	DL	1.03	2.8	R
1027	Hemorrhage	DL, polar, medial	3.76	18.3	R
1029	Stroke	DL	1.76	24.0	L
1053	Trauma	DL	0.92	291.1	R
2012	Tumor	DL, SM, ACG	1.46	3.8	R
		Right dorsolateral frontal			
1017	Stroke	DL, parietal	3.04	1.3	L
1041	Lobectomy	DL, IM	2.92	4.2	R
1054	Tumor	IM, DL, ACG	2.55	24.7	R
1055	Infarct	SM, DL	5.09	10.9	R
1067	Stroke	DL	0.84	21.0	R
2001	Stroke	DL, striatal	3.26	5.3	R
2024	Stroke	DL, striatal	1.74	2.5	R
		Inferior medial			
1023	Stroke	Striatal, caudate, IM (L), ACG (L)	0.85	26.7	Both
1056	Stroke	IM, ACG	1.60	33.1	Both
1059	Trauma	IM, DL, ACG	4.47	34.1	L
1065	Trauma	IM	1.30	15.6	R
1069	Tumor	IM	0.22	2.5	R
2013	Stroke	IM, septal, ACG	0.07	8.9	R
		Superior medial + (inferior medial)			
1011	Trauma	Medial, DL (L), ACG	7.17	13.9	R
1044	Hemorrhage	IM, polar, ACG, SM (L)	3.20	118.9	R
2002	Infarct	Medial, DL, ACG (L)	1.19	4.6	R
2011	Stroke	SM, ACG	1.60	3.6	R
2045	Stroke	Medial, septal, ACG	7.43	59.8	R
2167	Tumor	Medial, polar	5.46	6.0	R
		Nonfrontal			
1049	Tumor	Temporal (L)	na	17.8	R
1058	Stroke	Parietal (L)	na	3.5	R
2028	Stroke	Temporal, occipital (L)	0.95	28.5	R
2032	Lobectomy	Temporal (L)	1.60	49.6	R
2036	Lobectomy	Temporal (L)	na	91.3	R
2038	Lobectomy	Temporal (L)	1.17	144.7	R
2040	Lobectomy	Temporal (R)	2.06	89.3	R
2043	Stroke	Occipital (R)	0.48	36.3	R
2054	Lobectomy	Temporal (L)	na	142.6	R
2057	Lobectomy	Temporal (R)	2.66	134.6	R
2103	Stroke	Parietal, occipital (R)	0.74	34.6	R

Note. Percentage of lesion size for certain patients varies across studies by a minimal amount because of refinements in measurement. The variations do not alter any group differences. DL = dorsolateral; ACG = anterior cingulate gyrus; IM = inferior medial; R = right; L = left; SM = superior medial; na = not applicable.

feature); (f) focused attention, the ability to focus attention on one feature for target detection after completing a task requiring three-feature conjunction for detection—proportional change between redundant and complex tasks.

For each task, the means of RT (measured in milliseconds) to correct target and nontarget responses were measured. In all analyses, the first RT trial and trials with RT less than 150 ms were eliminated because either of these might reflect distorted RT. A proportional score, using the previous task as the reference, was used when comparing performance on two RT tasks. The proportional score has the advantage of investigating group differences in performance on a given task while adjusting for the processes involved in the comparative task. Group differences were investigated with a priori contrasts against the control group.

Error analyses. The number of different types of errors was also measured for each task. The types of errors analyzed included omissions (failure to respond to a stimulus), false positives (commission errors; the identification of a nontarget as a target), and

Table 2
Summary of Demographic and Clinical Data and NART–R Scores

Group (*n*)	Age (years)	Education (years)	Lesion size (%)	TSI (months)	NART–R
LDL (M 2, F 4)					
M	53.0	11.7	1.6	61.9	99.5
SD	11.3	0.8	1.1	112.9	7.4
RDL (M 5, F 2)					
M	56.9	10.1	2.8	10.0	101.9
SD	11.7	3.0	1.3	9.4	11.4
IM (M 5, F 1)					
M	46.2	10.5	1.4	20.2	100.5
SD	14.6	2.6	1.6	13.1	10.5
SM (M 4, F 2)					
M	58.3	11.5	4.3	34.5	98.6
SD	7.1	2.7	2.8	46.6	12.0
NF (M 3, F 8)					
M	42.7	13.1	1.4	70.3	106.4
SD	11.6	2.4	0.8	52.5	8.8
Control (M 6, F 6)					
M	53.5	13.6	na	na	115.3
SD	15.5	1.9	na	na	5.5

Note. NART–R = National Adult Reading Test—Revised; TSI = time since injury; LDL = left dorsolateral frontal; M = male; F = female; RDL = right dorsolateral frontal; IM = inferior medial frontal; SM = superior medial frontal; NF = nonfrontal; na = not applicable.

false negatives (identification of a target as a nontarget). The accuracy of task performance was investigated by looking for group differences in the number and types of errors. Because of the skewness in error distribution, errors were analyzed in the following manner: For each task, the trimmed maximum number of errors (the second-largest observation) in the control group was used as a threshold for detecting an abnormal number of errors. Patient groups were then analyzed to see if the proportion of subjects in each particular group who exceeded this threshold was greater than the proportion in the control group, using Fisher's Exact Test.

Complex task. Additional analyses were conducted within the complex task. First, the sensitivity and bias in target detection were analyzed for the complex as well as for the easy and redundant tasks. Second, the effect of varying amounts of shared features on speed and accuracy of RT was examined in the complex task using a repeated-measures analysis of variance, again with patient groups coded as a priori contrasts against the control group and including interactions with the within-subject (number of shared features) factor.

Statistical hypothesis testing was conducted at an alpha level of 5%. The number of subjects varied across analyses because of 2 subjects, 1 for whom the first simple RT data could not be retrieved from the computer, and the other for whom the complex RT data had not been collected.

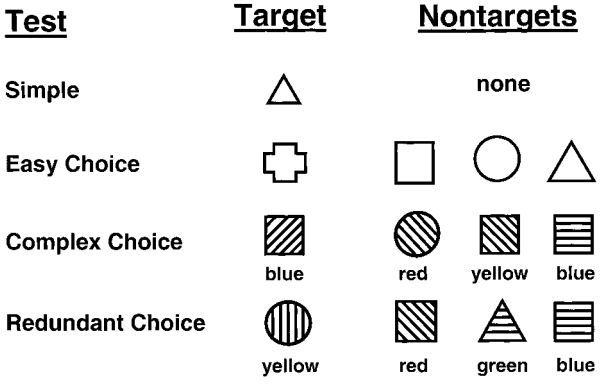

Figure 2. Depiction of the simple, easy, complex, and redundant reaction time tasks. For each task, examples of a target and of nontargets are shown where relevant. Identified color refers to the color of the stimulus.

Results

Although we attempted to equate the subject groups demographically, the following significant differences were found (see Table 2). The control group was more educated than the RDL and IM lesion groups, $F(5, 42) = 3.1$, $p = .02$. The control group scored significantly higher on an index of general intellectual functioning (NART–R) than all patient groups, $F(5, 39) = 4.4$, $p = .003$.

There were no significant group differences in time since injury ($p = .20$) among the five patient groupings, and no general effect of time post onset on simple RT. Average lesion size was not equal across the five patient groups, $F(4, 27) = 3.8$, $p = .01$. The SM group had the largest lesions—significantly larger than the NF and IM groups and marginally larger than the LDL group—but lesion size also had no general effect on simple RT. Patients with right hemisphere lesions were slightly slower than those with left hemisphere lesions across all tasks, but this difference was not significant. Thus, we found no effect of general hemispheric laterality.

RTs

The mean RT to correct target response for each of the five groups on the five tasks (adjusted for age, sex, and education to ensure that potential group differences could

not be unduly influenced by these variables) are presented in Figure 3. The SM group was significantly slower than controls on the simple RT task (given age, sex, education), $F(1, 38) = 7.6$, $p = .02$. The second simple RT task was proportionally slower than the first, $F(1, 38) = 4.7$, $p = .04$, but there were no group effects. For the following task comparisons, analyses of covariance were used to investigate group differences in the proportional change score, again controlling for age, sex, and education. The baseline measure was chosen to adjust for task features that were not of interest in each analysis. There was a significant proportional slowing from the simple task to the easy task, $F(1, 38) = 33.0$, $p < .01$. The LDL group, $F(1, 38) = 6.9$, $p = .01$, showed significantly greater proportional slowing from the simple to the easy task than the control group, whereas the IM group ($p = .07$) and SM group ($p = .07$) showed marginally greater proportional slowing. Although overall we found no significant proportional increase in RT from the easy to complex tasks, the SM group, $F(1, 38) = 6.3$, $p = .02$, LDL group, $F(1, 38) = 5.2$, $p = .03$, and IM group, $F(1, 38) = 4.7$, $p = .04$, showed significantly less proportional increase than the control group. Further, although we found no significant proportional decrease in RT from the complex to redundant tasks, the SM group, $F(1, 38) = 6.1$, $p = .02$, and LDL group, $F(1, 38) = 4.6$, $p = .04$, showed significantly less proportional RT decrease than the control group. There was also no significant group difference on the proportional change between easy and redundant tasks.

In summary, the RT measures revealed specific task effects. Although only the SM group was significantly slower than the control group on simple RT, the RDL group was marginally slower, and the IM group was nominally faster. The LDL group slowed excessively with the additional requirements of the easy task relative to the simple task. As evident in Figure 3, however, no group was significantly slowed by the extra requirements of the increase in difficulty of feature integration from the easy to complex task relative to the controls—the SM, LDL, and IM groups were in fact significantly less affected. The SM and LDL groups also benefited less from the opportunity to focus attention in the redundant task relative to the complex task.

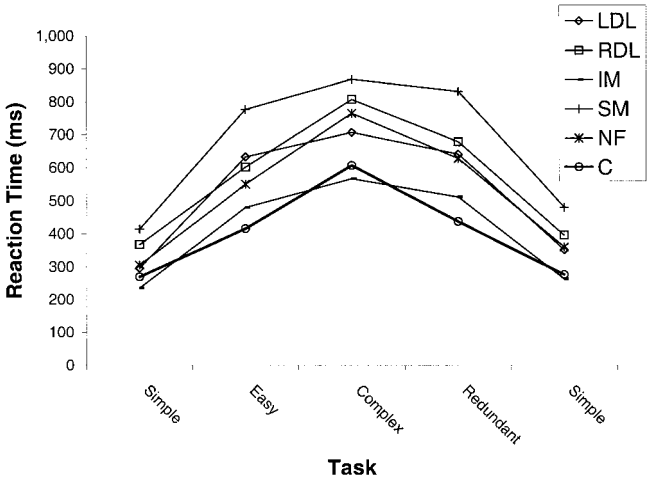

Figure 3. Average reaction times (RTs) of correct responses to target stimuli (adjusted for age, sex, and education) are presented for the first simple, easy, complex, and redundant discrimination RT tasks and the second simple discrimination RT task. The mean scores provide a pictorial image of the actual RTs for the different conditions; in the text, comparisons between conditions were completed with proportional scores to compensate for any group RT difference at the lower level of task. Groups are left dorsolateral frontal (LDL), right dorsolateral frontal (RDL), inferior medial (IM), superior medial (SM), nonfrontal (NF—left NF and right NF subjects were combined because their profiles were similar), and control (C).

Errors

There were no significant differences between groups in the proportion of subjects making more than one omission on the simple task.

On the easy task, a higher percentage of subjects in the RDL group (43%, $p = .04$) and the SM group (67%, $p = .005$) made omission errors, relative to the control group where no subject made any omission errors. In this same task, only in the RDL group were subjects significantly more likely to have an abnormally high false-positive error rate ($p = .04$); they also were somewhat more likely to have an abnormally high false-negative error rate ($p = .12$). On the complex task, a higher percentage of SM subjects (100%, $p = .005$) made omissions, relative to the control group where only one of the 12 (8%) made any omissions. Only the RDL group made significantly more false negative responses ($p = .05$) and false positives ($p = .02$). These same two groups made more errors related to the ability to identify nontargets (false positives), a significantly greater percentage of RDL subjects ($p = .02$) and a marginally greater percentage of SM subjects ($p = .10$) having false-positive rates exceeding the threshold. In this complex task, subjects in the LDL group were not found to be more likely to have abnormal error rates. When there was a trend, it was related to the ability to identify nontargets (false positives to nontarget stimuli), with a marginally greater percentage of the LDL group (33%, $p = .11$) having false positives exceeding the threshold rate relative to controls.

On the redundant task, a higher percentage of RDL (43%, $p = .04$) and SM (67%, $p = .005$) subjects made more than one omission, relative to the control group where no subject made more than one omission. On the second administration of the simple task, a higher percentage of SM subjects (67%, $p = .005$) made more than one omission, relative to the control group where no subject made more than one omission.

In summary, the error analyses suggest that abnormal error rates occurred after damage involving the RDL or SM areas, the errors for these two groups being of all types (omissions of both targets and nontargets, false positives, and false negatives). Patients with left frontal damage tended to make errors related to the nontargets only (false positives and nontarget omissions).

Analyses Within the Complex RT Task

Sensitivity and bias. False positive and false negative error rates can provide indices of sensitivity and bias. *Sen-*

sitivity is the ability to identify the target correctly by differentiating targets from nontargets. *Bias* refers to the criterion level set to identify a target as such. In contrast to the error analyses, which compared the proportion of subjects with abnormal error rates, in this section bias and sensitivity (functions of false positive and false negative rates) are compared with controls conditional on age, sex, and education. Significant group effects were observed on the complex RT task (see Figure 4). The average sensitivity of the control group on this task was 3.9, and their average bias was .19. The RDL group had a significantly lower mean sensitivity score (average $d' = 2.3$), $F(1, 38) = 7.8$, $p = .01$, than the control group (again conditional on age, sex, and education) but similar bias; average criterion level (c) = .19. In contrast, the LDL group had significantly different bias (average $c = -.21$), $F(1, 38) = 5.8$, $p = .02$, toward identifying stimuli as targets than the control group, but similar sensitivity (average $d' = 3.6$). The SM group exhibited bias and sensitivity that fell between LDL and RDL groups. The groups with NF or IM frontal lesions performed in a manner very similar to the control group.

On the redundant task, the RDL group was found to have decreased sensitivity, $F(1, 39) = 5.1$, $p = .03$, relative to the control group (2.7 vs. 3.8). On the easy task, the SM group was found to have decreased bias, $F(1, 39) = 4.9$, $p = .03$, relative to the control group (.19 vs. .50).

In summary, patients with left frontal damage identified virtually all targets as such, making few omissions or false-negative responses. Whatever errors they did make were due to a criterion-setting problem (bias toward identifying stimuli as targets), leading to false-positive errors. In contrast, patients with right frontal damage had trouble discriminating targets and nontargets, this sensitivity problem leading to errors of all types. The SM group fell in between, whereas altered bias was revealed in the easy task.

Effect of the Number of Features Shared by the Target and the Nontargets

Speed of RT. The control group's pattern served as the template for comparison to other groups (see Figure 5). Mean RT (adjusted for age, sex, and education) for the control group increased only slightly from 457 ms, for the nontarget sharing no features with the target, to 471 ms, for the one-shared-feature nontarget, and then increased to 576 ms for two-shared-features nontargets and then again slightly to 591 ms for target stimuli. Average combined RT to these distractors sharing zero, one, or two features (solid lines, top panel) was longer for the SM group, $F(1, 38) = 15.4$, $p = .0004$, LDL group, $F(1, 38) = 11.2$, $p = .002$, RDL group, $F(1, 38) = 8.2$, $p = .007$, and NF group, $F(1, 38) = 5.9$, $p = .02$, relative to the control group and adjusted for age, sex, and education. The effect of the number of shared features on RT was significant, $F(2, 76) = 5.3$, $p = .007$, but interactions with group were not.

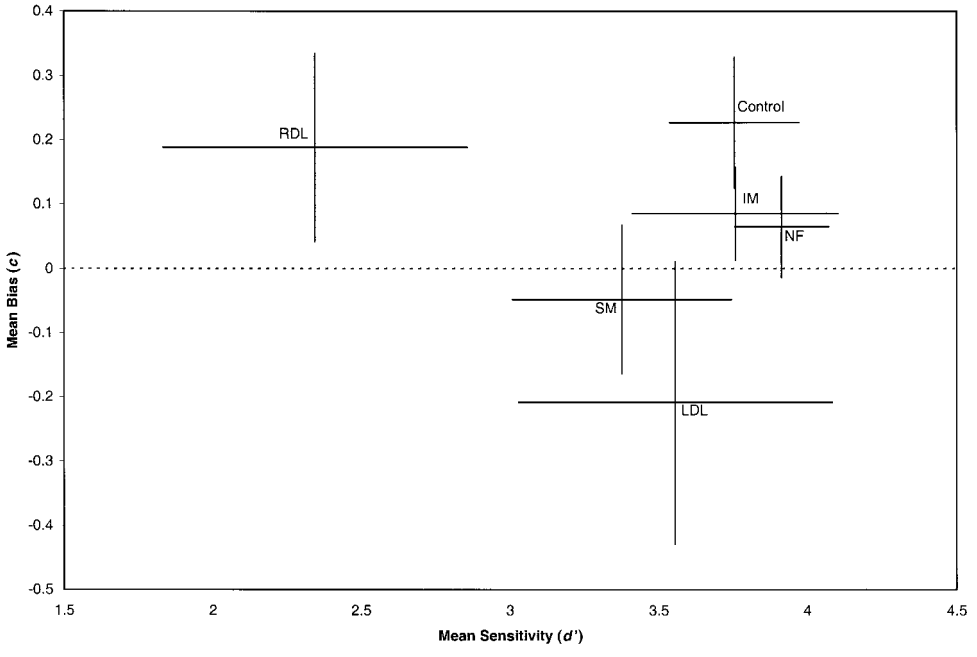

Figure 4. Bias and sensitivity across all groups for the complex reaction time (RT) task. Average bias, ranging from −2.33 (biased toward target button) to 2.33 (biased toward nontarget button), versus average sensitivity, ranging from 0 (unable to discriminate) to 4.65 (perfect accuracy), are illustrated for the control and five patient groups in the complex RT task. The RDL group shows decreased sensitivity but normal bias compared with the control and NF groups. The LDL group exhibits altered bias but normal sensitivity compared with the control and NF groups. RDL = right dorsolateral frontal; IM = inferior medial; NF = nonfrontal; SM = superior medial; LDL = left dorsolateral frontal.

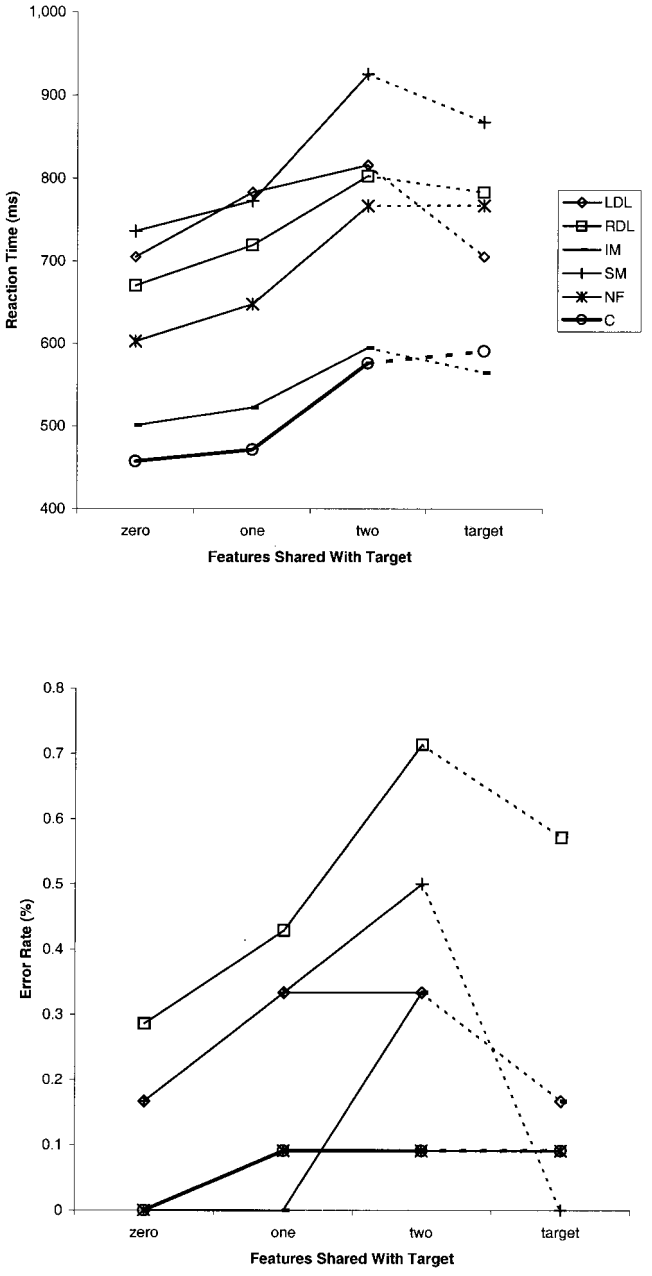

Figure 5. Effect of manipulating complexity within the complex reaction time (RT) task. The complex task nontarget stimuli are divided into those that share zero, one, or two features with the target. Results of each group for the targets (stimuli that were defined for each subject by a particular combination of the three features) are presented at the ends of the dotted lines. Average RT for each of these stimuli groupings is presented in the top panel, and the proportion of subjects with an error rate classified as abnormally high relative to the control subjects in the bottom panel. LDL = left dorsolateral frontal; RDL = right dorsolateral frontal; IM = inferior medial; SM = superior medial; NF = nonfrontal; C = control.

That is, as the number of shared features for the distracters was increased, average RT for all groups increased.

Errors. For each participant in the complex RT task, the proportion of incorrect responses to the nontarget stimuli (false positives) was computed for each category of nontargets on the basis of the number of shared features. The trimmed maximum (i.e., the second highest) error rate for the control group was used as the cutoff for normal performance. All of the control participants correctly rejected all of the stimuli with zero shared features as distractors, and therefore zero error rate was the cutoff for normal performance on these stimuli. The second highest error rates for the control subjects on stimuli with one and two shared features were 0% and 10.3% respectively. The proportion of control participants exceeding these cutoffs was 0% (for zero shared features) and 9% (for one and two shared features). The NF group's performance was not significantly different from that of the control group.

Figure 5, which depicts the changes at the subgroup level, shows that for the RDL and SM groups, the proportion of individuals with abnormal error rates compared with the control group increased as the number of shared features increased. At the level of two shared features, 71% (p = .01) of the RDL group and 50% (p = .10) of the SM group had abnormal error rates. In contrast, the prevalence of errors in the LDL group increased from the zero- to one-shared-feature level, but remained constant at the two-feature level at a rate of 33%, a final level that was also reached by the IM group.

The Role of the Anterior Cingulate Gyrus

To investigate further possible anatomical specificity and because of the reported importance of the cingulate gyrus in demanding attentional tasks, we divided frontal-damaged participants into those with (n = 12) and without (n = 14) ACG damage. RTs on the complex RT task were essentially equivalent (ACG = 722.5 ms; non-ACG = 740.7 ms, *SEM* = 57). Neither bias nor sensitivity was significantly different between frontal patients with and without ACG lesions, conditional or not on age, sex, and education.

Discussion

Different frontal regions are related to different attentional processes. These dissociations are revealed primarily through analyses within the complex RT task.

Speed of RT

Simple RT is not significantly compromised by focal brain damage in most regions of the brain at our level of lesion specificity when there is no motor weakness. This finding is not consistent with previous research suggesting that brain damage, independent of location, is associated with a general decrease in RT (Alivisatos & Milner, 1989; Audet, Mercier, Collard, Rochette, & Hebert, 2000; Benton & Joynt, 1959; Tartaglione, Bino, Manzino, Spadavecchia, & Favale, 1986). That there is no generalized effect of frontal lesions on simple RT might not be unexpected from a theoretical viewpoint. With simple RT, there is a constant mapping of the target. No selection or contingency planning is required. The appropriate response is invariable, and any programming required can occur before response initiation

(Klapp et al., 1979). There was, however, significant slowing associated with SM lesions and nonsignificant slowing of two other frontal groups, which might indicate a mild disruption of coordinating motor output (Salthouse, 1985), a role of the frontal motor association cortex (Fuster, 1999).

The absence of a significant group fatigue or practice effect on mean RT has been reported elsewhere for patients with frontal lobe damage or traumatic brain injury (Benton & Blackburn, 1957; Bruhn & Parsons, 1971; Costa, 1962; Godefroy et al., 1994; MacFlynn, Montgomery, Fenton, & Rutherford, 1984; Stuss et al., 1989). This minimizes the possibility that significant group differences on the more complex tasks that came later were secondary to an order effect or reduced motivation (Godefroy et al., 1994; Ward, Sharkey, Marston, & Brown, 1998). Decreased motivation and other general factors affecting task engagement might be more likely to occur in more demanding or sensitive tasks (Chapman & Chapman, 1973, 1978); in the present experiments, this would be the complex RT task. However, any generalized performance deficits cannot explain the functional–anatomical specificity of the results, unless one postulates that the impaired group is somehow specifically sensitive to such factors. The finding of brain-lesion-specific differences would still require postulating the association of some other process with that brain region.

Our initial hypothesis was that increasing task complexity would cause disproportionate slowing only in patients with frontal injury. The results were not so simple. Adding one level of processing complexity did have a significant effect on RT—but only for the LDL group (with statistically inconclusive slowing of the two medial groups) and only with what naively seems like a very small increase in complexity from the simple RT with constant target mapping to the easy RT, which requires simple feature differentiation and choice. Yet at the highest level of complexity requiring detection of three features in one target before responding, no group showed significantly disproportionate slowing.

This finding on the differential effects of complexity poses a challenge of interpretation. We have observed a similar effect in a previous study (Stuss et al., 1999). In a select what–respond where task, we compared measurements of interference, negative priming, and inhibition of return across groups of patients with different focal lesions. There were three levels of task difficulty. Patients with right frontal and bifrontal lesions (all medial lesions but with insufficient numbers for investigating separate IM and SM groups) showed a significant increase in RT with the presence of distracting information (interference) going from the first to the second level of difficulty, but not from the second to the third. Both studies demonstrated an effect of threshold complexity for patients with certain frontal lobe lesions, but the threshold for this effect is set at a low level, with no significant increase at higher levels of complexity. In our studies, the degrees of complexity were relatively limited, and our data cannot clarify if a flat threshold is held with ever-increasing difficulty. Perhaps there are multiple threshold levels set at different levels of complexity for frontal-damaged patients. The effect was observed in the bifrontal (probably SM) and either left (this study) or right (Stuss et al., 1999) frontal groups, suggesting a brain region–task specificity association.

One possible explanation of the threshold effect in this study is suggested by review of the task demands. For some groups, the threshold would be crossed as soon as any response selection is required. One difference between the simple and easy tasks is the requirement for selection between alternative choices in the easy task (this same difference between a constant stimuli–response mapping and a response selection was present in a previous study; Stuss et al., 1999). This is not required for the constantly mapped simple RT task. At this first level of response selection, only the LDL (and to a lesser degree the IM and SM) patients had difficulty. The potential role of the LDL and SM regions, at least, in response setting is reflected as well in our interpretation of the sensitivity and bias results below. Others have proposed that the LDL area is critical for setting response selection (Fletcher, Shallice, & Dolan, 1998; Shallice, 2002). Clearly, task demands have to be considered in the expression of this function, because in a select what–respond where task, with distractors present, the RDL region was most relevant (Stuss et al., 1999).

The major difference between the easy and complex tasks, on the other hand, appears to be one of levels of feature integration (response selection demands being equivalent between the two tasks). The absence of a significant disproportional group slowing because of complexity of correct feature integration argues that the frontal lobes do not participate in correct integration of features during detection. It is possible that the lesions in our patients did not involve the specific frontal–posterior connections underlying feature integration, but given the almost complete coverage of frontal systems in the subgroups, this is unlikely. It is also possible that hemifield presentation of stimuli might have brought out a specific lateral effect, but tasks of that sort have been carried out in patients with frontal lesions, and only working memory deficits have been demonstrated (Nielsen-Bohlman & Knight, 1999). Our conclusions cannot, however, be extended to studies of feature conjunction during visual search. Although not feature integration per se, there is evidence that, as monkeys learn arbitrary object–spatial associations, there is an accompanying change in prefrontal neural activity (Asaad, Rainer, & Miller, 1998; Bichot, Schall, & Thompson, 1996). Frontal activation in an fMRI experiment of conjunction search has been reported (Donner et al., 2000). Frontal-lobe single-cell recording in monkeys was reported in a visual search conjunction task, with increases in time of target discrimination occurring across difficulty levels (Bichot, Thompson, Rao, & Schall, 2001). In such instances, however, the role of the search process itself, or the visual selection during the search of possible targets from nontargets presented simultaneously, may be more relevant than true feature conjunction. Feature integration in visual search tasks may be bound through the object's location in an attended space (Treisman & Gelade, 1980). However, this cannot be the only mechanism, because conjoining features takes time even if the stimuli are presented with a known and attended location (Cortese, Bernstein, & Alain, 1999; Woods, Alain, & Ogawa, 1998), as in this study.

A. Cohen and Shoup (2000) had suggested that response selection for single-feature targets takes place separately and independently for different aspects of visual dimensions (e.g., shape, orientation) when a target is defined by a single feature. However, when the target is defined by several dimensions, then a single central conjunction map (which they suggest may be located in the frontal lobes) is constructed to enable the subject to search efficiently for a single conjunctive target, where response selection is formed. We did not examine this possibility experimentally. Nevertheless, our data would appear to be more compatible with a single, central response selection mechanism. In addition, the data would intimate that a central conjunction map, if present, was not located in the frontal lobes.

Previous studies have reported that patients with SM lesions may perform similarly to patients with either right or left lateral regions, depending on task demands (Stuss et al., 1998, Stuss, Levine, et al., 2000). There may be some functional overlap between SM and DL in each hemisphere; both emerge from the same archicortical developmental source (Pandya & Yeterian, 1996). SM lesions may also impair some general response activation (see discussion below). Thus, SM error profiles will resemble those of whichever DL region is more critical for implementing specific response schemas after general activation is achieved. In a verbal fluency study (Stuss et al., 1998), the similarity was maximum between the SM and LDL groups—as in the present study. In the investigation of the Wisconsin Card Sorting Test (Stuss, Levine, et al., 2000), the performance of the SM group was most similar to the RDL group—and in the present study, this was observed with the error analysis.

That the performance of the IM group is closest to the control group is not an unexpected result. We have previously shown no effect of IM damage on a broad range of cognitive and attention dependent tasks: verbal fluency (Stuss et al., 1998); the majority of measures on the Wisconsin Card Sorting Test (Stuss, Levine, et al., 2000); the Stroop Task (Stuss, Floden, et al., 2001); and the Trail Making Test (Stuss, Bisschop, et al., 2001). The functions normally mediated by this inferior or ventral medial region are those associated with the acquisition and reversal of stimulus–reward associations and high-level personal decision making and social behavior (Bechara, Damasio, Tranel, & Anderson, 1998; Dias, Robbins, & Roberts, 1996; Freedman, Black, Ebert, & Binns, 1998; Fuster, 1997; Levine, Freedman, Dawson, Black, & Stuss, 1999; Rolls, 2000), functions not assessed in our study.

Error Analyses

Errors were not due to a general lesion effect, because patients with lesions in the NF areas, the IM frontal area and, for most error measures, the LDL area were not significantly different from the control group.

Participants with right frontal lesions made the most errors. A significant number of patients in this group made excessive omissions on all three tasks (easy, complex, and redundant). The lack of complexity effect on errors in frontal-damaged patients had been noted earlier (Decary & Richer, 1995). A large percentage of the group with right frontal lesions also made excessive false-positive responses, a heightened responsiveness to distracting information noted in other research (Alivisatos & Milner, 1989; Knight, Hillyard, Woods, & Neville, 1981; Stuss et al., 1999; Woods & Knight, 1986). This impaired distinction between targets and nontargets has also been demonstrated in tests such as continuous performance tests, particularly with more complex targets (Glosser & Goodglass, 1990; Rueckert & Grafman, 1996). The importance of activation of the right frontal lobe in sustained attention to task has been demonstrated in healthy adults (Deutsch, Papanicolaou, Bourbon, & Eisenberg, 1987; Pardo et al., 1991). It is difficult to ascribe the marked decrease in sensitivity in the RDL group solely to a speed–accuracy trade-off. The RDL had significantly slower RT than the control group on the complex task. In a direct group comparison within the complex task, three groups were significantly slower than the control group—SM ($p = .003$), RDL ($p = .02$), and NF ($p = .04$) groups—but the NF group did not commit a significant number of errors.

The LDL group made more errors than the NF and control groups but fewer than the SM and RDL groups, although none of these differences were significant. Our results in the LDL group contrast with Godefroy, Lhullier, and Rousseaux (1996), who claimed effects of LDL lesions on simple RT and divided attention. Patients in that study, however, all had predominantly medial or polar damage because of infarctions in the anterior cerebral artery territory after anterior communicating artery rupture. That is, the lesions were more anterior and medial than in our group.

Sensitivity and Bias

The analysis of error types within the complex task has revealed, to our knowledge for the first time, a frontal lobe hemispheric distinction between sensitivity and bias. The patients with LDL damage were impaired in task setting, manifested as a defective criterion for responsiveness. In the left frontal group, the great majority of targets were identified correctly (few omissions or false-negative responses). This was achieved by an adjustment in criterion with a bias to identify any stimulus as a target. Errors were, therefore, predominantly false-positive responses. In contrast to the LDL task-setting problem, the patients with RDL damage had errors of all types, failing to discriminate both targets (omissions and false negatives) and nontargets (false positives)—a sensitivity problem.

The Effect of Shared Features in Nontargets

Gradually increasing the number of shared features between the nontarget and target stimuli allowed computation of the time required to process all the information in the stimulus and the probability of errors with increased interference. In the control group, there was minimal increase in RT and errors when the nontarget shared one feature with the target, but there was an increase with more shared features. The IM group had a very similar profile.

Error analysis indicated that minimally increasing the difficulty of stimulus analysis (zero to one shared feature)

affects, albeit nonsignificantly, only patients with frontal lesions, with the exception of the IM group. At a higher degree of difficulty (two shared features), only the RDL and SM groups showed an even greater proportion of impaired subjects than in the control group, the LDL group remaining constant. These data confirm the sensitivity of the RDL area and, to a somewhat lesser degree, the SM region to potentially distracting information.

The Anterior Cingulate Gyrus

Patients whose damage included the anterior cingulate were not, in this study, extremely slow, nor did they make an excessive amount of errors. Earlier theories have suggested an important role for the ACG in the modulation of attention and intention, particularly for complex tasks (Mesulam, 1981, 1990; Posner, 1988). The exact processes attributed to the ACG have varied, depending on the type of task used. For example, these included cognitively demanding tasks in general (Fletcher et al., 1995; Frith, Friston, Liddle, & Frackowiak, 1991; Rueckert & Grafman, 1996); monitoring and compensating for errors (Dehaene, Posner, & Tucker, 1994); online general performance monitoring independent of errors (Carter et al., 1998); selection of information for attention to action, particularly if inhibition of another competing response is required (Bench, et al., 1993; Pardo et al., 1990); and facilitating correct and suppressing inappropriate responses (Paus et al., 1993).

There are several possible reasons that acting singly or in combination may account for our failure to demonstrate a critical effect of ACG lesions. First, at a very fine-grained anatomical level, there is substantial functional heterogeneity of the ACG (Devinsky, Morrell, & Vogt, 1995). For example, in single-neuron recordings in the human ACG during attention-demanding cognitive tasks, only 19% of the ACG neurons tested were clearly modified in one or more attention tasks (Davis, Hutchison, Lozano, Tasker, & Dostrovsky, 2000). Our lesion analysis techniques are too coarse to detect such fine regional distinctions. Second, there is modification of the effects of ACG lesions over time. Janer and Pardo (1991) found attentional dysfunction in a cingulotomy lesion case study only in the subacute postoperative stage, with no deficit at 6-month reexamination. The majority of patients in the present study were investigated in the chronic phase of recovery, and we may have simply missed a critical window. Third, many of the claims for specific functions of the ACG come from functional imaging in normal control subjects. ACG activation may not be induced by performance of the actual task but by some unifying, but underlying, preparation activity (Taylor, Kornblum, Lauber, Minoshima, & Koeppe, 1997). Our results did demonstrate a general slowing effect of lesions in the SM regions, many including the ACG and the supplementary motor area. It will be important to pursue greater anatomical specificity in the roles of discrete anatomical zones within this broad region.

Consideration of Potential Moderating Factors

These specific attentional impairments after frontal lesions are not due simply to diminished motivation (Ward et al., 1998) or apathy (Stuss, van Reekum, & Murphy, 2000), at least as evidenced by the lack of fatigue effect for simple RT. The sample size is relatively large compared with most other focal lesion studies, particularly considering the care taken to select patients with lesions reasonably limited to frontal or NF areas. Potential confounds such as age, education, lesion size, and time since injury were addressed during design and analysis stages. A peripheral motor explanation, as proposed by Godefroy and Rousseaux (1996a) for binary decision processes, is unsatisfactory considering the negative RT findings on the effects of complexity across tasks. The problem also cannot be a generalized slowing that affects all stages of processing, because there were differential speed–accuracy effects depending on the lesion location and no direct relation between impairment and complexity.

Another potential explanation for our findings, particularly the right frontal deficits, is impaired working memory (keeping the features in mind for target discrimination). Courtney, Petit, Haxby, and Ungerleider (1998), for example, postulated that there is a right–left frontal difference for image-based (right) and analytical (left) tasks requiring working memory. There are two arguments against a general working memory basis. First, the various attentional control processes associated with the frontal lobe are dissociable from working memory. D'Esposito, Ballard, Aquirre, and Zarahn (1998) compared working memory and nonworking memory tasks to a rest condition. They concluded that the "reverse inference 'if prefrontal cortex is active, working memory is engaged' is not supported" (p. 274). This is an important distinction: The same brain regions may be involved in separate tasks, but it does not follow that a single process (working memory) is involved. The second argument against a general working memory explanation is embedded in the test design; the demands for maintaining active representation of information over a delay in the absence of sensory input were minimized. The information stayed on the screen for an extended time, the patient was asked what the features were at the end of the task, and there was no evidence of forgetting the rule. Finally, errors occurred on even the easy task, where the working memory demands are minimal.

Conclusions

Attention is divisible into multiple components (Godefroy et al., 1996). Analogous to the component processes in the posterior attentional system (Posner, 1988), our data indicate separable processes in the anterior attentional system, related to different regions of the frontal lobes (see also Pardo et al., 1991; Posner, Petersen, Fox, & Raichle, 1988). The absence of a significant effect of complexity on correct feature integration suggests that these frontal attentional functions extend beyond feature discrimination, spatial representation, hemispatial orientation, or feature integration—the attentional functions of posterior brain regions demonstrated in lesion and imaging studies (Bernstein & Robertson, 1998; Corbetta, Shulman, Miezin, & Petersen, 1995). The posterior pa-

tients in our study were not impaired, because the extent of parietal lobe damage was minimal.

We suggest that the current, as well as earlier, findings of attentional impairments after frontal lesions define three separable anterior attentional systems and that a model previously proposed for the cognitive architecture of attention provides a framework for these results (Stuss et al., 1995). One attentional system maintains a general state of readiness to respond. This is the fundamental operation of the SM frontal regions. The current findings confirm previous results on the role of the SM frontal region in performance of the Stroop Incongruent Task (Stuss, Floden, et al., 2001). If the general maintenance of attentional activation is a role of medial frontal structures, the relative contribution of ACG to this activation is uncertain. Many imaging studies in normal subjects have suggested a major role for the ACG in attention (e.g., Bench et al., 1993; Botvinick et al., 1999; Carter et al., 1998; Pardo et al., 1990), but the study of patients with focal medial lesions has not always confirmed a unique role for the anterior cingulate (Stuss, Floden, et al., 2001). The functional imaging research indicates some role of the anterior cingulate, but its exact nature is undetermined.

A second attentional system sets the criterion level to respond to a target (or, in other contexts, some external stimulus). The criterion level establishes a bias for responsiveness. In this study, only damage to the LDL region produced abnormal bias. This is a deficit in setting attention to respond.

The third anterior attentional system maintains the selection of the defined schema so that consistent target selections are made, and responses to competing targets are inhibited. The more similar the nontarget to the target, the more likely the collateral excitation of the nontarget, and the more difficult the inhibitory role. The RDL region appears to be necessary to maintain distinctions between targets and nontargets. Reduced maintenance of this discrimination leads to errors of all types, measured as poor sensitivity. In this study, RDL lesions caused increased errors of all types. This is a deficit in sustaining attention to criteria. J. D. Cohen and Servan-Schreiber's (1992) early observation supports our conclusion that the prefrontal lobe is necessary to maintain task demands, but we demonstrated that this is not a general effect of prefrontal lesions. Deficits in sustaining attention to criteria are specific to the right lateral frontal lesions. It is also possible that this same general region is important in inhibition of irrelevant information.

These proposed effects of lesions in specific regions of the frontal lobes on attention have obvious consequences for performance on a variety of tasks that may not commonly be viewed as "attentional"—verbal fluency, categorization, sequencing. The different types of attentional impairments contribute to failure on a broad range of tasks, but, just as working memory deficits are not the basis for every "executive" impairment, the attentional disorders described here are only part of the complex sum of processes that define the role of the frontal lobes.

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