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RESPONSE SELECTION DEFICITS IN FRONTAL EXCISIONS

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Abstract—We compared the performance of patients with frontal excisions, patients with temporal excisions and controls in tasks involving speeded choice responses in which a number of variables were manipulated including: perceptual difficulty, stimulus and response set-size, associative complexity, and spatial stimulus-response compatibility. Response times were sensitive to all manipulations but did not show any group differences. The error rates of the three groups were equally affected by perceptual difficulty and response set-size but frontals were preferentially affected by spatial S-R compatibility, associative complexity, and the number of stimuli per response. The results are consistent with a basic deficit in response selection processes which could underlie many problems produced by frontal lesions.

Key Words: frontal excisions; response deficits; response selection.

INTRODUCTION

Lesions in the frontal lobes have long been associated with behavioral control problems [4, 13, 15, 31]. However, the frontal contribution to the cognitive processes underlying behavioral control or executive functions is still not well understood partly because it manifests itself in such a wide variety of symptoms. Patients with frontal lesions show control problems in the attentional sphere with symptoms such as distractibility and concentration difficulties [9, 12, 13]. They also show poor control of task-relevant responses which can be observed in tasks requiring sequential responses, changes in response set, or inhibition of a habitual response [10, 13, 17, 20, 25, 27]. The cognitive control problems of frontals can also be expressed as deficits in the fluency or efficiency with which correct responses are retrieved [2, 15, 19], or as planning difficulties in complex situations [15].

It has yet to be determined whether few or numerous elementary processes participate in the generation of these varied symptoms. There are of course obvious difficulties in the analysis of symptoms in humans because of the variability in the extent and location of the lesions. However, the cognitive control deficits observed in frontals in complex situations share a number of common aspects and some may be critical to the production of various deficits presently considered as independent. For example, most of the tasks in which frontal patients have shown difficulties involve the retrieval or selection of a response among alternatives based on the context or instructions of the task. However, little is

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known of the effects of frontal lesions on response selection or decisional processes. Frontal patients show difficulties in learning arbitrary conditional associations between stimuli and responses when the number of S–R associations is above 5 or 6 [6, 23, 24, 28]. In monkeys, lesions in premotor cortex are associated with problems in learning conditional associations involving as few as two responses [7, 17, 21, 22]. However, these observations do not indicate whether the critical aspect of the deficit is in the acquisition of the conditional associations or if patients with frontal lesions would also show response selection problems for known S–R associations.

If frontal lesions affect response selection processes they should impair performance of simple conditional responses in which the S–R mapping is known and the number of alternatives is small. Deficits have been observed in tasks such as the detection of rare auditory events [33], or the detection of rare novel stimuli among repetitions of a stimulus [29]. Frontal excisions also produce problems in the search of multiple target stimuli in sequences and this deficit cannot be accounted for by their psychomotor slowing nor by their ability to remember the target stimuli [27]. However, these tasks differ from standard conditional response tasks in many respects and it is not clear whether the main cause of the deficit in these tasks is faulty decisional or response selection processes.

The aim of the present study was to directly investigate the effect of frontal lesions on conditional responses to find evidence of a basic deficit in response selection, i.e. in choosing the correct response to a stimulus when the associative rule is known. Because frontal patients generally don't show much difficulty applying a simple rule to choose between two alternatives at a very slow pace, we examined the execution of rapid choices among two or four alternatives. Patients with unilateral frontal lesions were compared to temporal-lesioned patients and controls. In these tasks, frontal patients remember the associative rule but difficulties can arise in correctly applying the rule under time pressure. We expected patients with frontal lesions generally to make more errors on rapid choices, but this could have several causes. A response selection deficit should appear as a specific sensitivity to manipulations of associative or decisional variables such as stimulus-response compatibility and the complexity of the associative rule and not to manipulations of non-associative variables such as the perceptual complexity of the task.

METHODS

Subjects

We compared the performance of eight patients with a unilateral frontal excision (six right, two left) to that of eight patients with a unilateral temporal excision (four right, four left) and of eight controls with no history of cerebral damage. Groups were comparable in age (Frontals: 41 years, Temporals: 38 years, Controls: 37 years; range: 26–55 years) and education level (Frontals: 11 years, Temporals: 11 years, Controls: 12 years; range: 6–18 years). All the resections were performed in adulthood to alleviate a drug-resistant epilepsy. They were all tested at least 1 year following the surgical intervention. For all subjects, informed consent to participate in the study was obtained according to the rules of Hôpital Notre-Dame.

Frontal excisions were variable in extent but always included dorsomedial structures (anterior cingulate gyrus, superior frontal gyrus including supplementary motor area) and a variable amount of dorsolateral cortex anterior to the precentral sulcus. Figure 1 shows the extent of the frontal resections. Seven of the frontal patients showed a marked reduction in seizure frequency after surgery (80% or more), two were seizure-free and all were on anticonvulsant medication. Anterior temporal excisions involved resection of the anterior portion of the temporal lobe (about 5 cm from the anterior tip of the lobe), partial resection of the hippocampus, and sparing of Heschl's gyrus. All temporal patients showed a marked reduction in seizure frequency (four were seizure-free) and four

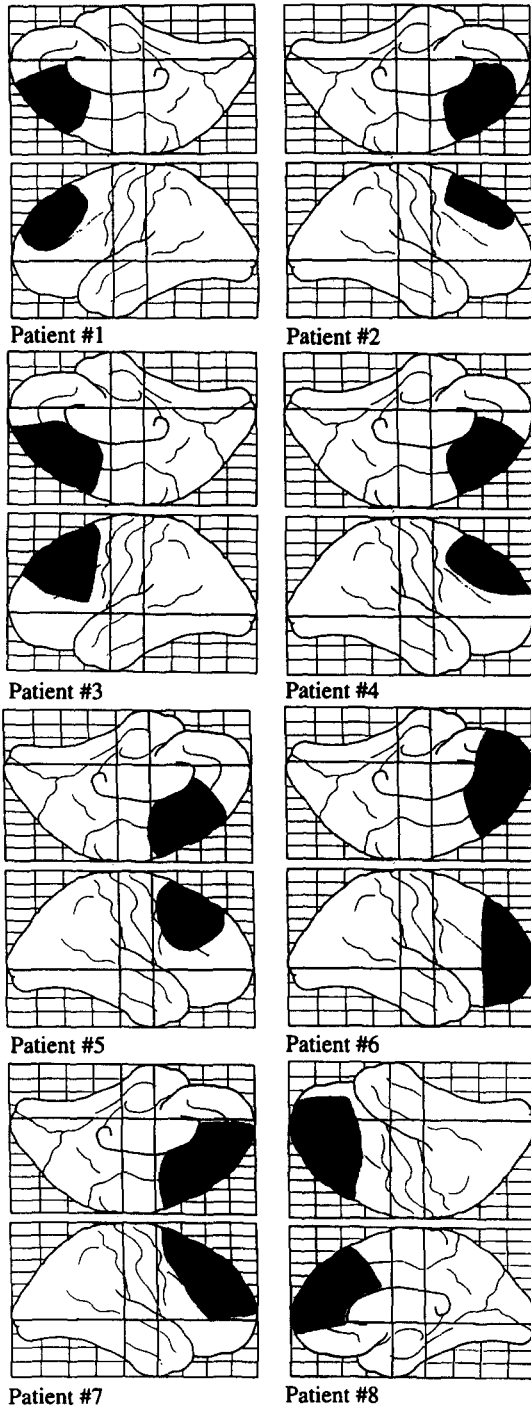


Fig. 1. Extent of medial and lateral resection of the frontal excisions.

were still on anticonvulsant medication. All of the patients underwent post-surgery neurological and neuropsychological evaluations and none exhibited sensory or motor impairment on standard clinical measures.

Tasks and procedure

Subjects were tested in tasks involving speeded responses to visual stimuli. The tasks were given in a fixed order. For each task the S-R association rule was explained to the subject and its comprehension was verified through appropriate questioning. All aspects of the tasks were controlled by a 486 computer with Neuroscan software. Stimuli were 5 × 7-cm symbols presented for 750 msec on a monitor in white on a black background and were viewed at a distance of 1.0 m. In each task, subjects received 20 practice trials followed by two blocks of 40 trials separated by a short break. Stimuli were presented in a pseudo-random sequence with a stimulus-onset asynchrony of 3.0 sec. An error tone was delivered whenever an error occurred and response latencies above 1200 msec were considered omissions. Response times and errors were recorded.

Control tasks. Subjects were tested in two control tasks, a simple response task designed to observe their response time when no choice is involved, and three Go-NoGo response tasks designed to test their tendency to respond impulsively in speeded response situations. In the simple response task, subjects were asked to press a response key as fast as they could each time a square appeared at the center of the screen. In Go-NoGo response tasks subjects were asked to press a key to the presentation of one symbol (\square) and not to respond when other symbols (\square , \square , \square , \square) were presented. Subjects were tested in three versions of the Go-NoGo response task, one in which Go and NoGo trials were equiprobable, a second version in which the probability of Go trials was 0.15 and that of NoGo trials was 0.85 and a third version in which these two probabilities were inverted (0.85 for Go trials, 0.15 for NoGo trials). This manipulation was used to test whether frontals showed impulsivity in rapid conditional responses which should be observed as a sensitivity of the false response rate to response probability.

Non-spatial choice tasks. Subjects were then tested in a series of non-spatial choice tasks in which different symbols had to be associated to either of two or four keypress responses. A two-choice task was used as baseline to compare the effects of various manipulations. In this baseline task, subjects were asked to press one of two adjacent keys (R1 vs R2) as quickly as possible depending on the symbol presented. Four equiprobable symbols were associated to the two responses with a simple S-R mapping rule (\dot{d} or $\dot{d} = R1$; \dot{d} or $\dot{d} = R2$).

The following tasks examined various manipulations of this baseline task.

(A) Perceptual difficulty was manipulated by applying a 70% degradation on the stimuli (random removal of 70% of pixels). This manipulation is known to affect RT and error rates but does not interact with manipulations of response selection difficulty [30, 31].

(B) The number of stimuli per response was increased so that six symbols were mapped to each of the two responses instead of two ($\dot{d} \dot{d} \dot{d} \dot{p} \dot{p} \dot{p} = R1$; $\dot{d} \dot{d} \dot{d} \dot{p} \dot{p} \dot{p} = R2$). This manipulation has been shown to affect response selection [8].

(C) The third manipulation affected the complexity of the decision or association rule. The S-R association rule was made conjunctive by mapping symbols \dot{d} and \dot{p} to R1 and \dot{d} and \dot{p} to R2. Whereas in the baseline task, the stimuli could be segregated by the number of hyphens they contained (two or not two), with the conjunctive rule subjects had to determine the position of the hyphens in relation to the orientation of the letter presented simultaneously. This manipulation of the complexity of the S-R mapping rule has a strong effect on response selection difficulty [16].

(D) The number of response alternatives was increased to four, each mapped to two symbols with a simple S-R mapping rule (\dot{d} or $\dot{p} = R1$; \dot{d} or $\dot{p} = R2$; \dot{d} or $\dot{p} = R3$; \dot{d} or $\dot{p} = R4$). Although early work had attributed the effects of this manipulation on performance to response selection processes, there is evidence that response preparation processes may account for most of its effects when the mapping rule is kept simple [5, 11].

Spatial choice tasks. One of the most investigated manipulation of response selection processes is the spatial compatibility between stimuli and responses [1, 3, 26]. We thus examined whether frontals were preferentially affected by S-R compatibility in two spatial choice tasks involving four alternatives. On each trial, the stimulus was a 4-cm² white square appearing in one of four positions on the monitor (left, middle left, middle right and right) and each position was mapped to one of four response keys aligned from left to right. In the baseline task, the S-R mapping was spatially compatible or direct; in the second task, the S-R mapping was made spatially incompatible by associating each location of the square with its symmetrically opposite response key.

RESULTS

Table 1 presents the response times of the three groups in all tasks while Table 2 shows their error and omission rates. These measures were analyzed by two-factor ANOVAs examining the effects of a given manipulation as well as group differences. In Go-NoGo tasks, the manipulation examined was response probability (0.15, 0.50, 0.85). In non-spatial choice tasks, the effects of the various manipulations were examined using the

Table 1. Average response latencies (msec) of the three groups on the various tasks (S.D.)

	Frontals	Temporals	Normals
<i>Control tasks</i>			
Simple responses	331 (105)	320 (130)	235 (30)
Go-NoGo prob=0.5	541 (73)	523 (90)	462 (40)
Go-NoGo prob=0.15	599 (82)	535 (80)	494 (65)
Go-NoGo prob=0.85	506 (83)	485 (99)	425 (44)
<i>Non-spatial choice tasks</i>			
Two-choice baseline	660 (64)	635 (81)	599 (56)
Degraded stimuli	777 (67)	792 (82)	736 (57)
6 S per R	695 (64)	661 (67)	635 (42)
Conjunctive rule	707 (46)	681 (70)	675 (40)
Four response alternatives	746 (50)	688 (52)	655 (41)
<i>Spatial choice tasks</i>			
Compatible four-choice	625 (72)	569 (71)	538 (64)
Incompatible four-choice	740 (92)	677 (93)	635 (81)

two-choice baseline task as comparison. In the spatial choice tasks, the manipulation examined was S-R compatibility.

Response times

Control tasks. In simple speeded responses involving no choice, response times (RT) did not differ significantly among the three groups [$F(2, 21) = 2.3$, n.s.]. In Go-NoGo tasks, RT was significantly affected by response probability [$F(2, 20) = 17.9$, $P < 0.001$]. However, there was no significant group difference [$F(2, 21) = 3.2$, n.s.] nor a significant interaction between group and response probability [$F(4, 40) = 1.0$, n.s.].

Non-spatial choice tasks. The response times of the three groups did not differ significantly in the baseline two-choice task [$F(2, 21) = 1.8$, n.s.]. As expected, all the manipulations examined in non-spatial choice tasks significantly increased RT [all $F(1, 21) > 20.6$, all $P < 0.001$]. Significant group differences were not observed in the two-factor analyses [all $F(2, 21) < 2.3$, n.s.], except for the manipulation of the number of response alternatives [$F(2, 21) = 4.3$, $P < 0.03$] and this was due to the difference between frontals and normals [$F(1, 21) = 8.5$, $P < 0.01$], the other contrasts were not significant [$F(1, 21) < 2.3$, n.s.]. Also, none of the manipulations examined showed a significant interaction with group on the RT measure [all $F(2, 21) < 1.5$, n.s.].

Table 2. Average error and omission rates (%) of the three groups on the various tasks (S.D.)

	Frontals		Temporals		Normals	
	Errors	Omissions	Errors	Omissions	Errors	Omissions
<i>Control tasks</i>						
Simple responses	—	—	—	—	—	—
Go–NoGo prob=0.5	1.9 (2.1)	—	0.6 (0.9)	—	0.16 (0.4)	—
Go–NoGo prob=0.15	2.8 (2.0)	—	0.3 (0.6)	—	0.16 (0.4)	—
Go–NoGo prob=0.85	4.2 (3.9)	—	1.1 (0.8)	—	0.3 (0.6)	—
<i>Non-spatial choice tasks</i>						
Two-choice baseline	7.8 (5.5)	3.6 (6.7)	3.6 (2.3)	1.7 (2.1)	1.7 (2.2)	0.5 (0.6)
Degraded stimuli	25.3 (13.2)	13.7 (11.2)	12.2 (10.3)	14.1 (14.4)	9.2 (6.0)	5.3 (4.6)
6 S per R	14.4 (6.6)	4.2 (4.8)	4.4 (3.5)	1.9 (1.3)	1.9 (1.3)	0.17 (0.4)
Conjunctive rule	35.5 (17.4)	5.6 (2.6)	4.3 (2.4)	2.8 (3.2)	5.3 (4.3)	1.6 (2.1)
Four response alternatives	9.1 (6.3)	12.0 (8.0)	4.4 (4.8)	1.9 (2.5)	3.0 (2.3)	1.6 (1.4)
<i>Spatial choice tasks</i>						
Compatible four-choice	4.5 (2.8)	8.6 (9.5)	1.4 (1.5)	3.0 (4.0)	2.0 (2.2)	1.7 (1.7)
Incompatible four-choice	16.4 (13.8)	21.8 (14.5)	3.0 (3.3)	8.8 (10.3)	2.2 (3.4)	4.2 (6.0)

Spatial choice tasks. RT was significantly different among the groups in the spatial choice tasks [$F(2, 21) = 4.8, P < 0.02$], and this was due to the difference between frontals and normals [$F(1, 21) = 7.1, P < 0.01$], the other contrasts were not significant [$F(1, 21) < 2.7, n.s.$]. As expected, RT was affected by the S–R compatibility manipulation [$F(1, 21) = 39.1, P < 0.0001$] but there was no significant interaction between group and compatibility [$F(2, 21) = 1.8, n.s.$].

Error rates

Control tasks. None of the subjects made errors in simple responses. Frontals made more errors in all Go–NoGo response tasks [$F(2, 21) = 13.7, P < 0.002$]. However, error rates were not significantly affected by response probability [$F(2, 21) = 1.3, n.s.$] and there was no significant interaction between group and probability [$F(4, 40) < 1.0, n.s.$]. This indicates that although frontals always made more errors than the other two groups, they were not preferentially affected by response probability.

Non-spatial choice tasks. Frontals made significantly more errors than the two other groups on the baseline two-choice task [$F(2, 21) = 6.1, P < 0.01$]. The manipulation of perceptual difficulty produced a significant group effect [$F(2, 21) = 8.4, P < 0.002$] along with a significant task effect [$F(1, 21) = 30.6, P < 0.0001$], but no significant interaction [$F(2, 21) = 2.4, n.s.$]. The manipulation of the number of response alternatives (from 2 to 4) also produced a significant group effect [$F(2, 21) = 6.0, P < 0.01$], but neither the task effect [$F(1, 21) = 1.2, n.s.$] nor the interaction [$F(2, 21) < 1.0, n.s.$] were significant. Thus,

frontals were not preferentially affected by either perceptual difficulty or the number of alternatives.

The manipulation of the number of stimuli per response (from 2 to 6) produced a significant group effect [$F(2, 21) = 15.4, P < 0.0001$] along with a significant task effect [$F(1, 21) = 12.8, P < 0.002$]. A significant interaction (see Fig. 2) was also found [$F(2, 21) = 8.6, P < 0.002$] and simple effects revealed that frontals were the only group significantly affected by the manipulation [$F(1, 21) = 29.3, P < 0.0001$]. Similarly, the manipulation of the complexity of the associative rule produced a significant group effect [$F(2, 21) = 34.3, P < 0.0001$] along with a significant task effect [$F(1, 21) = 23.7, P < 0.0001$]. A significant interaction (see Fig. 2) was also obtained [$F(2, 21) = 15.5, P < 0.001$] and simple effects showed that frontals were the only group for which error rate was affected by the complexity of the associative rule [$F(1, 21) = 47.7, P < 0.0001$].

Spatial choice tasks. In the spatial choice tasks, error rates were significantly different among the groups [$F(2, 21) = 10.7, P < 0.0006$], due to differences between frontals and the other groups [$F(1, 21) > 8.1, P < 0.01$] and the manipulation of S-R compatibility produced a significant task effect [$F(1, 21) = 7.9, P < 0.02$]. The interaction between compatibility and group (see Fig. 2) was also significant [$F(2, 21) = 5.1, P < 0.02$] and simple effects showed that frontals were the only group in which error rates were significantly affected by S-R compatibility [$F(1, 21) = 17.7, P < 0.0004$].

Response omissions

In addition to increasing response times, some manipulations also increased the rate of omissions which in the present study were defined as non-responses or responses that were slower than 1200 msec. This was the case for perceptual difficulty, the number of response alternatives, and spatial S-R compatibility [all $F(2, 21) = 8.5, \text{all } P < 0.01$]. Frontals made more omissions than other groups in all the four-choice tasks, including the four-alternative non-spatial choice task and the two spatial conditional response tasks [all $F(2, 21) > 6.1, \text{all } P < 0.01$] but not in the other tasks [all $F(2, 21) < 1.5, \text{n.s.}$]. As described earlier, these four-choice tasks were the only ones in which frontals were also slower than the other groups.

Response times of errors in frontals

Frontals made significantly more errors than other groups in several of the tasks. To examine how the incorrect response trials differed from the trials producing a correct response, we compared the response times of incorrect responses to that of correct responses in the conditions in which error rates permitted this comparison. If errors were significantly slower than correct responses, it would suggest that they represent trials that were 'cut short', i.e. trials in which more processing time may have produced a correct response. On the other hand, if errors are as rapid or more rapid than correct responses, it would suggest that errors were due to factors other than slowed processing. Comparisons revealed that correct responses were faster in three of the four tasks in which they could be examined: the degraded stimulus task [$t(7) = 5.4, P < 0.001$], the conjunctive rule task [$t(7) = 3.1, P < 0.02$], and the task with 6 stimuli per response [$t(7) = 4.1, P < 0.01$], whereas no significant difference was observed in the incompatible spatial choice task [$t(7) < 1.0, \text{n.s.}$].

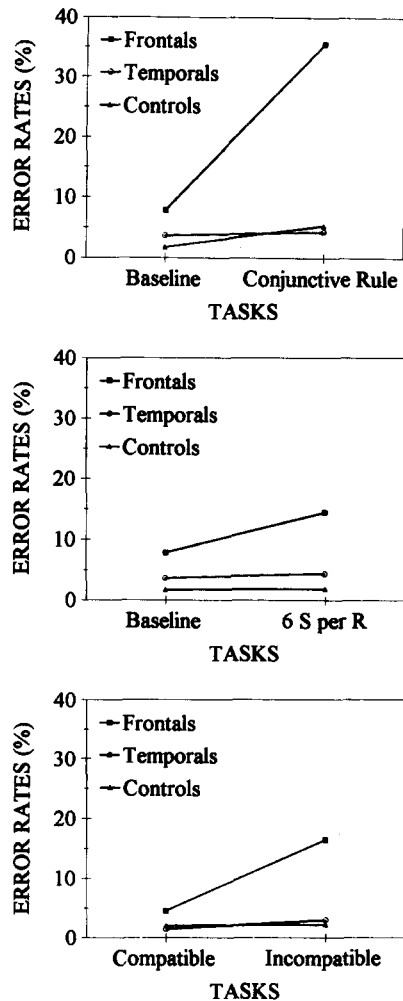


Fig. 2. Effects of three manipulations of response selection difficulty on error rates in the three groups examined.

DISCUSSION

This study was designed to investigate the difficulties of patients with frontal lesions in rapid choices. The deficits observed cannot be attributed to motor problems as all responses were easily executed by all subjects, nor to general slowing because the response times were often similar in the three groups and errors were generally not slower than correct responses. Also, the results cannot be explained as a general difficulty in response inhibition or impulsivity because on Go<NoGo tasks, although frontals made more errors than the other subjects in these tasks (as in all choice tasks), their error rate was not preferentially affected by the probability of responding. Impulsive responses in Go–NoGo tasks appear to be more characteristic of ventral frontal lesions and our patients showed mostly dorsal lesions [14].

In the present study, frontal patients showed specific increases in error rates to manipulations of response selection difficulty such as spatial S–R compatibility, the number of stimuli per response, and especially the complexity of the association rule. On the other hand, the manipulation of perceptual difficulty which was specifically designed to strongly increase RT and error rates in all subjects while keeping the S–R mapping rule simple, did not preferentially affect frontals. Also, increasing the number of response alternatives from two to four while keeping the S–R mapping rule simple did not preferentially affect the performance of frontals. To the extent that this manipulation affected the number of responses to prepare [5], it appears that frontals are not preferentially sensitive to response preparation manipulations, although this hypothesis should be tested directly in further studies.

The examination of rapid choices in frontals allowed us to show that they were preferentially affected by manipulations of decisional difficulty. The presence of a temporal constraint is probably an important factor in the observation of the present deficits, as frontals would probably make much fewer errors with no time pressure. Frontals showed their preferential sensitivity to decisional difficulty through error rates and not through increased RTs. Frontals showed normal RTs except in four-choice tasks in which they showed longer RTs and more omissions than normals. In these tasks, longer response windows may help reduce the rate of omissions of frontals.

The present results suggest that frontals show a basic difficulty in decision-making or response selection that can be revealed through speeded response tasks. The deficit observed here is not a learning deficit but one of applying an associative rule since patients knew in advance and remembered the associative rule for each task. The associative learning problem previously observed in frontals for a large number of alternatives [6, 24, 28] may be due to the response selection problem observed here, or a separate associative learning deficit may be present in frontals. The two problems have a great deal in common. For instance, unlearned six-alternative conditional associations and speeded conditional responses with a complex S–R mapping share a relatively low strength of S–R associations which could make defects in some associative control processes appear more clearly. However, more research will be needed to examine the degree to which the two deficits are common or distinct.

The response selection problem of frontals could also underly a number of their difficulties in other complex tasks. This deficit could certainly affect the performance of frontals in tasks involving changes in response sets since these tasks involve choices with a variable S–R mapping rule. Complex response selection processes are also present in tasks involving response competition such as the Stroop task. They are also part of sequential response tasks in which the previous response of the subject can be considered as a stimulus for selecting or retrieving his next response. Of course, these tasks all have a number of other important features that may contribute to the deficits observed and future studies will have to examine the extent to which the decisional difficulties of frontals account for the poor behavior in these tasks.

The present results suggest that the mechanisms responsible for the correct processing of particular S–R associations are disrupted by frontal lobe lesions. The data do not indicate a total failure of response selection processes in frontals. Frontals are of course able to make many choices in everyday life. The data suggest that their response selection processes are inefficient, in that they can be disrupted much more easily than others by conditions which tax decisional mechanisms such as the temporal constraints of the choice

and the complexity of the S–R mapping. Frontal lesions may affect response selection mechanisms in a variety of ways. For example, errors could be caused by changes in the disruptibility, accuracy, or speed of processes involved in linking the correct S–R mapping rule to the present stimulus or of processes involved in monitoring the validity of the decision before the execution of the response. The exact nature of this inefficiency and the specific aspects of response selection processes that are sensitive to disruption in frontals will have to be examined in future studies. Finally, the frontal lobes are probably not the only structures contributing to response choice in complex S–R mapping contexts and future work should also address the contribution of other structures linked to frontal cortex in response selection processes.

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