TOWARD A COGNITIVE ACCOUNT OF FRONTAL LOBE FUNCTION: SIMULATING FRONTAL LOBE DEFICITS IN NORMAL SUBJECTS

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Toward a Cognitive account of Frontal-lobe function:
Simulating frontal lobe deficits in normal subjects

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Over the past twenty years, considerable progress has been made on characterizing the mental processes underlying higher level cognition. In particular, there now exists a number of detailed models and theories of the cognitive processes underlying problem solving, reasoning, and concept acquisition.[1,2,3] While these models were being developed, there also emerged a literature indicating that patients with frontal lobe damage exhibit a wide variety of deficits in reasoning, problem solving, and concept acquisition.[4,5,6] Surprisingly, little attempt has been made to link the cognitive research with the brain-based research. One of the reasons for this is that there has not, as yet, been a specification of the cognitive processes that underlie higher-level cognition and how higher-level cognitive processes are related to the attentional and working memory deficits implicated in frontal patients. The goal of the work reported in this paper is to begin to articulate the mechanisms that mediate higher-level cognition and specify their relationship to the deficits observed in patients with frontal lobe injury.

Perhaps the most striking and consistent impairment documented in frontal lobe cases is the difficulty they encounter on a variety of reasoning tasks.[7,8] In one task - the Wisconsin Card Sorting Test (WCST)- the patient is shown four cards placed in a row, each displaying geometric figures varying in terms of color, shape and number. The patient is then given a pack of 128 cards containing exemplars from the same categories as those represented in the four cards on display. He or she is told that the examiner has a particular undisclosed sorting criterion in mind (say color) which has to be discovered by assigning each card to one member of the target set. The examiner indicates whether the response is right or wrong, and the patient must use this information to minimize the number of placement errors. Frontal patients show a clear impairment on this task relative to patients of comparable IQ with left or right posterior lesions. Researchers have found that (a) Frontal patients achieve fewer categories than controls, (b) they make more perseverative errors than controls, and (c), they tend to make more perseverative than non-perseverative errors. It should be noted that some researchers have found that some frontal patients show little or no impairment on the WCST and have failed to find differences in performance between frontal patients and patients with other types of brain damage.[9] [10] Furthermore, researchers have found non-frontal patients and normal controls can show perseveration on the WCST.[11] Despite these findings, the WCST is still widely used as a diagnostic tool to measure frontal injury.

A number of different explanations have been offered for performance on this task. Milner[5] argued that frontal patients perseverate because they have an inability to overcome previously reinforced responses. More recently, researchers have offered cognitive reasons for the performance of frontal patients. For example, Shallice and his colleagues have argued that frontal patients have a deficit in the allocation and supervision of attention,[12] and Baddeley has argued that their deficit is a working memory deficit.[13] In particular, he has argued that frontal patients have a deficit in the Central Executive component of working memory -- this is the component of working memory that performs mental operations, and controls other working memory systems. Baddeley's model of working memory is not universally accepted; other researchers have argued for a more unitary working memory.[14,15] However, the Baddeley model makes it possible to derive a number of clear predictions regarding frontal patients and has been widely used in the literature on frontal patients. In this paper, we will use the Baddeley model because of it allows us to make clear experimental predictions; we are not committed to his model of working memory.

The hypothesis that perseveration on the WCST is due to a failure of the Central Executive has not been directly tested. Nonetheless, this hypothesis has been used to account for the performance of patients. Furthermore, current theories of performance on the WCST do not make it possible to determine precisely how the Central Executive is deficient in patients with frontal deficits. Thus, there are a number of different types of Central Executive deficits that might produce the same performance: Subjects might not attend to feedback, lose track of feedback, be unable to integrate information etc. Furthermore, while classic frontal performance is consistent with a Central Executive deficit, it is possible that other types of working memory deficits underlie this type of performance.[16] Finally, recent research demonstrating that non-frontal patients can show perseveration on the WCST further clouds the issue of what this task measures, and how the frontal lobes are involved in the task.[9]

One of the problems that prior accounts of the WCST have had is that the accounts have not been based on a cognitive analysis of the task. When the WCST is looked at as a classic concept attainment task in which patients must induce new concepts from sets of examples, it becomes clear that there are a number of different possible sources of perseveration.[3,17] Subjects have to keep in working memory the current hypothesis, feedback from at least the current trial, and also compare feedback to the current hypothesis on every trial. When the feedback is inconsistent with the current hypotheses, patients must be able to notice it, generate another hypothesis and compare that to the current feedback, and continue to generate hypotheses until they find an hypothesis that is consistent with the current feedback and if possible, recent feedback. Clearly, the task involves maintaining different types of information in working memory, and conducting various computations on the feedback in order to give correct responses. Potentially, many different types of memory and or attentional deficits could be involved in performing this task.

The goal of the research reported here was to investigate the memory mechanisms underlying perseveration. Currently, we know that frontal patients and other patients perseverate, but not what processes underlie this performance. To investigate these issues we used non brain damaged patients. Our hypothesis was that if working memory deficits underlie perseveration, then it should be possible to induce perseveration in normal subjects. To do this, we used a "dual task" methodology in which normal subjects were given the WCST and were asked to perform a working memory task at the same time as performing the WCST. In dual task terminology, the WCST is known as the "primary task" and the working memory task is known as the "secondary task." The secondary tasks that we used were tasks that take up different amounts and different types of working memory capacity. By manipulating the types of secondary tasks given to subjects we can investigate whether working memory deficits do indeed underlie perseveration, and if so, what types of working memory are involved in perseveration.

The tasks that we chose were selected in terms of Baddeley's model of working memory.., Baddeley has proposed that there are three main types of working memory; The Central Executive, The Phonological loop, and Visuospatial sketch pad. The Central Executive is the component of working memory that coordinates and controls the maintenance and flow of information in and out of working memory. The Phonological Loop maintains phonologically based information in working memory. The visuo-spatial scratch pad maintains visual representations of information. Baddeley has devised many different tasks that selectively take up one type of working memory while sparing the other type. Thus, his framework provides a specification of the types of tasks using one type of working memory and not another. Using Baddeley's model, we designed secondary tasks that can take up different types of working memory capacity while performing the WCST. The main manipulation was whether the secondary task took up Phonological Loop, or Central Executive. The reason for choosing tasks that took up these types of working memory capacity is that a task analysis indicates that the WCST involves both phonological memory (to store the current hypothesis, feedback, and perhaps prior instances) and the Central Executive (for allocating attention to, and performing operations on, the contents of the phonological loop).

Experiment 1

Three groups of subjects were tested. A control group who received The WCST alone, and two Experimental groups (a Phonological and a Central Executive group). Both experimental groups heard a tape of digits and then a tone. Subjects in the phonological group had to recall all digits when they heard the tone. Subjects in the Executive group had to give the sum of all numbers heard prior to the tone. The digit recall task is primarily a phonological task: Subjects have to maintain a set of numbers in memory, and this should be phonologically based. There were some executive components, in that the subjects did have to update their memory set after each digit was heard. However, the task should primarily tap phonological memory. If the WCST involves a phonological component, then the phonological task should produce a deficit in performance on the WCST. The addition task was primarily a Central Executive task as subjects had to update their memory, add the two digits, and store the result after each digit was heard. In this condition, there were more computations that needed to be performed than in the Phonological condition, yet the memory load was minimal. It was expected that subjects in the Executive condition would show performance that was more "frontal-like" than subjects in the Phonological condition. That is, these subjects should achieve few categories, and show more perseverative than non-perseverative errors.

Method

Subjects. Three groups of 12 subjects participated in the experiment. All were McGill undergraduates who participated in the experiment for course credit.

Procedure. Subjects in the experimental conditions heard a tape of digits with each digit presented once every three seconds. A tone was presented randomly, once every 4, 5, or 6 digits. In the phonological condition, subjects repeated the number when they heard it. When the tone occurred they had to repeat all numbers heard since the previous beep. In the Central Executive condition subjects heard the same tape, after hearing a number, they added the number to the previous number. They added each new number until they heard a beep. After the beep, subjects said the grand total, then began adding from zero with the next set of numbers.

While performing the number recall or number addition tasks, subjects performed the WCST. The WCST was presented on a computer.[18] Subjects used a mouse to select the key card under which the stimulus card was placed. When the subject clicked under the key card, the stimulus card appeared directly below the key card and the next card appeared at the top of the deck. As soon as the card was placed, the word correct, (if the response was correct), or incorrect (if the response was incorrect) appeared under the card. This feedback stayed on the screen until the subject placed the next card. The same order of categories and cards was used as in the non-computerized version of the WCST. Categories were given in the following order; Color, Form, Number, Color, Form, Number. When subjects had achieved 10 correct responses in a row, the sorting category was changed. If subjects achieved all 6 categories before they had used all 128 cards, the experiment was terminated. If subjects failed to achieve all 6 categories by the time 128 cards were used, the experiment was also terminated.

Results and discussion

The data were automatically analyzed by the computer using the same criteria as found in the Heaton norms.[19] The data that we will focus on is number of categories achieved, number of perseverative errors, and number of non-perseverative errors. Subjects can achieve a maximum of six categories. Perseverative errors are errors in which the subjects sorts according to a dimension even though feedback indicates that this is the incorrect sorting dimension. A non-perseverative error is an error in which the subject sorts along an incorrect dimension and this dimension is not the same as the previous incorrect response.

The number of categories achieved by subjects in each of the three groups was calculated. A one-way Analysis of Variance (ANOVA) revealed significant differences between the three groups in terms of number of categories completed [$F (2,32) = 17.82$, $P < .001$]. Post hoc tests indicated that all three conditions were significantly different from each other with the subjects in the Phonological condition achieving the least number of categories. The results for this experiment, and those of the Milner[5] and Heaton[20] -who used frontal patients- are given in Table 1. Comparing our results to those obtained with frontal patients indicate that subjects in the Phonological condition obtained the fewest categories, and looked most like frontal patients.

Insert Table 1 about here

The results for perseverative errors mirror those for number of categories. A one way ANOVA showed that subjects in the phonological condition had more perseverative errors than the Central Executive and control groups [$F(2,32) = 23.59$ $p<.0001$]. An ANOVA of non-perseverative errors revealed a significant effect of condition [$F(2,32) = 6.56$ $p<.01$]. Post hoc tests revealed that there were no significant differences between the Central Executive and Phonological groups, but that both of these groups had more non-perseverative errors than the control group. We also analyzed perseveration for the second category. The second category is the first time that a category is changed, and should have more perseverative errors than for the other categories. An ANOVA of the difference between perseverative and non-perseverative errors in the second category revealed a significant effect of condition [$F(2,31) = 3.9$, $p<.05$]. Post hoc comparisons revealed that only subjects in the Phonological condition had significantly more perseverative than non-perseverative errors. They had more perseverative errors than non-perseverative errors, and their absolute numbers of perseverative errors were similar to those obtained from frontal patients.

The results of this experiment were surprising: The Phonological task produced more perseveration, and subjects achieved fewer categories, than in the Executive task. Furthermore in the Phonological task there were more perseverative than non-perseverative errors, whereas in the Executive task there were more non-perseverative than perseverative errors. These results may indicate that the locus of perseveration is not in the Central Executive component of working memory, but is in Phonological working memory. Another possible interpretation of these findings is that neither of tasks tapped solely the Central Executive or the Phonological loop: The phonological task may have involved Central Executive components (such as updating the items maintained in the phonological loop) and, the Central Executive task may not have been demanding enough to produce perseveration.[20] We conducted a second experiment in which subjects had to perform either a pure phonological task, or a pure Central Executive task to further determine the roles of these types of working memory in the WCST.

Experiment 2

Two different secondary tasks were used in Experiment 2. One was an articulatory suppression task in which subjects had to say “the..the...the” continuously while performing the WCST. Baddeley and his colleagues have frequently used this task and have argued that it prevents subjects from rehearsing information in the articulatory loop.[21] For a more pure version of a Central Executive task, subjects were given a tone detection task. In this task, subjects heard a tone, and as soon as they heard the tone, they had to press a pedal with their foot. The tone was presented randomly. This task involves dynamically allocating resources to a secondary task, and can be described as a pure Central Executive task, or as a task in which subjects must switch attention between tasks. This task should not tap phonological memory, nor is it requiring the storage of information by working memory. For this task, we varied whether subjects used their right or left foot to press the key. Given that motor planning has been implicated in the left pre-frontal dorsolateral cortex, we hypothesized that subjects using the right foot might show more perseveration than subjects using the left foot .

Method

Subjects. Two groups of 11 McGill undergraduates were paid $5.00 to participate in the experiment. All subjects were right handed and stated that they were also right footed.

Procedure. In the Articulatory suppression condition subjects said "the-the-the-the" in a continuous stream while doing the WCST. There was no minimum speed required as long as subjects were constantly articulating. In the tone detection task subjects heard a beep coming from the computer at random intervals between 750-1850 ms [750, 850, 950....or 1850 ms]. Subjects were told that as soon as they heard the tone they were to press the foot pedal.

Results

One way ANOVAs were conducted of all the basic measures of performance revealing no significant differences between the three groups in: Number of categories achieved [F (2,30) =.81, p>.05], Number of perseverative errors[F (2,30) = 2.58, p>.05], and Number of non-perseverative errors [F(2,30) = .42, p>.05]. As the results of Experiment 1 indicated that the bulk of perseveration occurred for the second category, we conducted further analyses of perseverative and non-perseverative errors for the second category. There was an effect of condition on the difference between perseverative and non-perseverative errors [F(2,27) = p>.05]. Post hoc tests reveal that there were significantly more perseverative than non-perseverative errors in the articulatory suppression condition. There were no other significant effects, although it should be noted that subjects in the right foot condition did have more perseverative than non-perseverative errors, though this difference was not significant. For the left foot condition, there was no evidence of any difference in numbers of perseverative and non-perseverative errors.

Insert Table 2 about here

The results of this experiment indicate that at a global level, there were no significant differences between subjects in the three groups. However, an analysis of errors in category 2 revealed that subjects in the articulatory suppression condition did show more perseverative than non-perseverative errors.[22] A post experiment interview with subjects indicates that after the second category they developed strategies for coordinating the two tasks. Thus, more perseverative than non-perseverative errors only showed up for the second category. There was a non-significant trend in the direction of more perseverative than non-perseverative errors for the right foot condition, indicating the possibility of a Central Executive component to the task. The results for the second category performance are consistent with the hypothesis that perseveration in the WCST is the result of a deficit in maintaining information in the phonological loop, rather than a Central Executive deficit.

Experiment 3

The results of Experiments 1 and 2 indicate that it is possible to obtain perseveration when the phonological coding of information is prevented. These results make it possible to predict that patients with a deficit in phonological working memory should show perseveration on the WCST. Usually, patients with these types of deficits are not given the WCST, and the question as to whether patients with a phonological working memory deficit will show perseveration on the WCST is not asked. Experiment 3 was conducted to test this hypothesis.

We investigated this hypothesis by testing patient RoL of Belleville, Peretz, & Arguin (1992).[23] This patient has a lesion in the left temporoparietal region and has conduction aphasia. Belleville et al. have investigated this patient extensively and have argued that his main deficit is an articulatory rehearsal deficit. They found that on a variety of memory task his performance was similar to that of normal subjects given tasks that interfere with articulatory rehearsal. Furthermore, they found that when he was given tasks that in normal patients interfere with articulatory rehearsal, there was no further decrease his performance. Thus, this patient has a pure case of an articulatory rehearsal deficit. The findings of the first two experiments indicate that a patient such as this should also show deficits in performance on the WCST.

Method and Results

Patient ROL was administered the WCST. He obtained 0 categories, showed 94 perseverative errors, and 2 non-perseverative errors. He was administered the WCST a second time and was told that the categories will change. Even in this situation he still obtained only one category. Thus, his performance indicates that indeed an articulatory rehearsal deficit can produce perseverative errors

Summary of Simulation Experiments

The results of the three experiments reported so far indicate that it is possible to produce frontal-like performance in normal subjects. Using a dual task methodology, normal undergraduates formed less categories, made many errors, and made more perseverative than non-perseverative errors than control subjects. The performance of these subjects was very similar to that reported in the literature on frontal patients. Surprisingly, the conditions under which the most perseveration was obtained were phonological conditions. We further investigated the hypothesis that perseveration is the result of phonological deficits by testing a patient known to have a deficit in phonological processing and found that the performance of this patient was typical of that reported for frontal patients. Thus, we found further evidence for a potential phonological etiology of perseveration on the WCST.

The results of these experiments help explain why other researchers have questioned the validity of the WCST as a diagnostic tool. Recently, a number of labs have shown that patient populations other than frontal patients also display perseveration.[24,9] One possible reason that these other patients' perseveration is that their deficits may involve phonological working memory, and that it is deficits in phonological memory that lead to perseveration. While the phonological deficit hypothesis can explain much of the performance in the three preceding experiments, we also found a non-significant trend toward perseveration when subjects were given a more pure Central Executive task with no memory load. These results suggest that another possible mechanism underlying perseveration is that a Central Executive deficit may prevent patients from maintaining information in phonological working memory and thus cause perseveration in an indirect manner. Thus, it is still necessary to explore the role of the Central Executive. In the next two experiments we investigated one function of the Central Executive - the allocation of attention in patients with frontal deficits.

Experiments with Frontal Patients

While many authors have argued that frontal patients have a deficit in the Central Executive, what the Central Executive actually is, is somewhat shrouded in mystery. Baddeley has argued that it controls the flow of information in and out of the Phonological Loop and the visuo-spatial sketch pad. One way of describing it would be to say that it controls the allocation of attention to specific tasks and processes. Given that many authors have implicated this type of working memory/attentional allocation in frontal deficits, the goal of the research reported here was to investigate the question of whether frontal patients do in fact have an attentional allocation deficit and precisely how this affects thinking and reasoning.

To test the hypothesis that frontal patients have a deficit in the allocation of attention, we used a variant of the Stroop task.[25,26] In the Stroop task, subjects see a word, such as the word red in green ink. There are two sub-tasks involved in the Stroop task -- a color naming task and a word reading task.[27] In the color naming task the subject is required to name the ink color and ignore the word. In the word reading task, the subject is required to read the word and ignore the ink color. The typical findings are that the word interferes with ink color naming, but the ink color does not interfere with word reading. The usual interpretation of this data is that word reading is an automatic process and is involuntary, causing interference with word reading.[28] Conversely, color naming is thought to be a controlled or voluntary process, and hence does not interfere with word reading. This task has been used with Frontal patients, with mixed results. Perret has shown that in color naming, frontal patients show more interference than controls.[29] However Shallice was not able to obtain differences between frontal patients and controls on this task.[30] If Perret's results hold, then it would be consistent with the hypothesis that frontal patients cannot inhibit a well learned or automatic process. The first goal of the research reported here was to use the Stroop task to see whether frontal patients do in fact show increased interference. Once we have obtained baseline information on the Stroop task, we can then use a novel version of the Stroop task that can be used to investigate whether frontal patients have deficits in attentional allocation.

We used a version of the Stroop task known as the picture-word interference task.[31] In this task the subjects see a stimulus such as a picture of a "horse" with a word typed on the picture, for example the word "cat." In the word reading task, subjects must read the word and ignore the picture. In the picture naming task, subjects must name the picture and ignore the word. Just as in the standard Stroop color naming task, picture naming is thought to be less automatic than word reading, and thus the word interferes with picture naming, but the picture does not interfere with word reading. Thus, the picture-word task is equivalent to the standard color naming task. We used this task, rather than the color naming task, as it allows us to manipulate a wide variety of semantic and categorical variables that are not possible to manipulate using the standard color naming task.

Experiment 4

In this experiment we used the picture-word task to determine whether frontal patients show more interference than normal subjects. A further goal of the experiment was to determine whether frontal patients are more subject to interference from words that are potential responses than control groups. Recall that one explanation for frontal deficits is that their deficit is one of inhibiting well learned responses. If this is the case, frontal patients should not only show more interference than controls, they should also show more interference from words that are potential responses, than words that are not potential responses. However recent simulations by Jonathan Cohen using the Cohen, Dunbar and McClelland model of attention predicts that a disturbance in the mechanisms of attentional allocation should reduce the size of the response set effect, such that non-response set members produce more interference relative to response set members[21,32]

To test these predictions we varied the relationship between the pictures and the words. For example, the pictures that the patients name might be horse, bear, rabbit, sheep, and cat. Patients would see one of these five pictures on every trial. What would be varied is the type of word superimposed on the picture. The words that are potential response would also be horse, bear, rabbit, sheep, and cat. Words that are not potential responses might be dog, goat, seal, donkey. In normal subjects words that are potential responses produce around 25 milliseconds more interference than non-potential responses. If the deficits that frontal patients have is one of inhibiting responses, then we would expect them to show much more interference from words that are potential responses than words that are not potential responses. If the deficit is one of allocating attention --as the Cohen, Dunbar, & McClelland model predicts[26]-- then we would expect no more interference from words that are potential responses than words that are not.

The patient population that we used were Frontal Closed Head Injury patients. These patients all had frontal head injuries and hare similar to patients used in a number of studies of frontal lobe function. However, it should be noted that data obtained from Closed Head injury patients is more difficult to interpret than that obtained from patients with focal frontal lesions: Closed Head Injury patients also have widespread white matter lesions. We attempted to circumvent this problem by only using patients who obtained 3 or less categories on the WCST, had an IQ in the range of 100, and obtained normal scores on naming and memory tests.

Method.

Subjects. Five patients with frontal closed head injuries were used. All five patients obtained three or less categories on the WCST and had a mean IQ of 103.

Procedure. The patients were tested on Macintosh plus computer. The stimuli were the digitized pictures of horse, rabbit, bear, cat, and sheep.[33] There were four conditions. In the control condition the pictures had a row of 4 X's superimposed upon them. In the Congruent condition, the word was the same as the picture. In the incongruent same set condition, the words were from the same set as the pictures, and the word and picture were never the same. In the incongruent different set, none of the words were from the same set as the pictures. The words were dog, mouse, donkey, goat, & seal. Subjects were given a block of 120 trials. Each block consisted of 30 trials of each of the four types of stimuli, randomly intermixed. Each trial consisted of a subject seeing a fixation point in the middle of the screen for 150 ms, then the picture-word stimulus appeared. The stimulus stayed on the screen until the subject named the picture or three seconds had elapsed. Reaction time was measured from the onset of the picture word stimulus to the onset of the verbal response.

Results and Discussion

Block 1 was considered to be a block of practice trials that introduced the subjects to the response set and was not analyzed. A one way ANOVA was conducted on reaction time for blocks 2-4. There was a significant difference between conditions [$F(3,15) = 16.7$, $P<.001$]. As can be seen from Table 4, subjects did show interference in both the incongruent same set and incongruent different set conditions. However, as predicted by recent simulations using the Cohen, Dunbar, & McClelland model,[26] there was no difference between same set and different set conditions. Furthermore, the amount of interference that the patients showed was between 94-97 milliseconds. This was within the range reported for normal subjects.

Insert Table 3 about here

Overall, the patients in this experiment showed neither more interference than normal subjects nor any more interference from words that are potential responses than words that are not potential responses. These results suggest that these patients did not have a deficit in inhibiting responses. The results are consistent with the CDM model of attention, indicating that these patients have a deficit in attentional allocation. This data is also consistent with that recently reported by Vendrell et al [34]. Using the Stroop task, they found that frontal patients do not show more interference than controls. Having obtained this baseline information, we can now turn to a more direct test of whether the deficit that frontal patients have is one of the allocation of attention and begin to answer the question of how this leads to deficits in performance on higher-level cognitive tasks.

Experiment 5

The goal of the research reported in this experiment is to determine whether frontal patients do indeed have a deficit in the allocation of attention. Recently, we have conducted a number of experiments in which we have investigated how normal subjects allocate attention.[35] We used a version of the Stroop task in which subjects do not know whether their task is to name an ink color or read a word until they hear a tone. We have used conditions in which the tone indicating which task to perform occurs either at the same time as the Stroop stimulus, or 400 milliseconds prior to the Stroop stimulus. In both of these conditions, subjects demonstrated that it takes them time to allocate attention to the task, and that unlike the normal version of the Stroop task, ink color interferes with word reading. This task makes it possible to directly investigate the allocation of attention, and should make it possible to investigate attentional allocation in frontal patients.

We developed a picture-word version of the allocation task for use with frontal patients. In this task, patients do not know whether the task that they must perform is a word reading or picture naming task until they hear a tone. Subjects hear a tone 400 milliseconds before the picture-word stimulus appears. The tone indicates which task to perform. Note that subjects have to wait until they hear the tone before they begin allocating all their attention to one task rather than the other. Thus, the task is concerned with one of the core components of the Central Executive-- allocating mental capacity to a task. When the task is given to frontal patients, a number of outcomes are possible. First, subjects might not be able to allocate their attention appropriately. In particular, patients may allocate attention to the most automatic process- word reading. If this is the case, patients should make many errors in the picture naming task, and show increased interference with picture naming. If patients have this type of deficit, they should also have few errors in word reading, and little interference with word reading. A second potential outcome is that frontal patients will not be able to allocate attention appropriately, and will randomly pick which task to perform. This outcome would occur if their deficit is one of allocating attention. A third possibility is that , as in Experiment 4, patients will be able to execute both tasks with only a small error rate and be similar to normal subjects.

Method

Subjects. A different set of 5 subjects, from the same population as the previous experiment, were used. These subjects were also administered the Experiment 4 version of the picture-word tasks, after they had been given Experiment 5. This manipulation was conducted to ensure that the patients showed the same effects as in Experiment 4, which they did.

Procedure. The stimuli were the pictures horse, rabbit, bear, sheep, and cat. The words were also horse, bear, rabbit, sheep and cat. There were three types of stimuli, Congruent, Incongruent, and control items. Congruent items were where the words and pictures were the same (e.g., the word horse on a picture of a horse). Incongruent items were where the words were different from the picture (e.g., the word cat on a picture of a horse). Control items for the picture naming task consisted of the pictures with a row of X's. For the word reading condition control items consisted of a word surrounded by a geometric figure. The experiment was a 2x2 design with factors of Task (color naming or word reading) and Congruency (congruent, incongruent or control). There were 144 trials: 72 picture naming, and 72 word reading. There were 24 congruent, 24 incongruent, and 24 control trials. On each trial subjects saw a fixation point for 500 milliseconds, the screen went blank, and 100 milliseconds later they heard one of two tones. The tone lasted for 100 milliseconds. 400 milliseconds after the offset of the tone the picture-word stimulus occurred and the patient had to name the picture, or read the word, depending on what type of tone occurred. A high pitched tone indicated that the task was to name the picture, and a low pitched tone indicated that the task was to read the word.

Results and Discussion.

Two ANOVAs were conducted, the first was on reaction time data, and the second was on error data. Both ANOVAs were 2X3 with factors of Task (picture naming, or word reading), and Congruency (Congruent, Incongruent, or Control). The reaction time ANOVA revealed no differences between picture naming and word reading nor between the three levels of congruency. The reason why there were no effects becomes clear when we look at the error data. There was a main effect of congruency, with subjects performing at chance [F92,8) =27.39, P <.01]. A graph of this effect is shown in Figure 1. Here it can be seen that in the Incongruent condition for both picture naming and word reading, subjects made errors on almost 50% of the trials. Thus, on half the picture naming trials the patients were reading the word, and on half the word reading trials they were naming the pictures. In the congruent condition, given that the word and the picture were the same, it did not matter which dimension the subject responded to, the response would always be correct, and less errors occurred. In the control condition the irrelevant dimension was not easily namable, and thus did not produce as large a number of errors as in the incongruent condition.

Insert Figure 1 about here

Overall, the results of this experiment indicate that frontal patients do indeed have a deficit in attentional allocation. When there was uncertainty as to what was the correct task to perform, and the patients had to dynamically allocate attention to tasks subjects chose tasks at a level close to chance. This data is thus consistent with the hypothesis that frontal patients have a deficit in allocating attention on the basis of constantly changing incoming information.

General discussion

The results of the five experiments reported in this paper indicate that there are a complex set of interactions between lower level cognitive processes, such as those involved in working memory and attentional allocation, and the higher-level cognitive processes that they subserve. By analyzing a complex task such as the Wisconsin card sorting task, it was possible to determine that the task involves both the temporary storage of information in a phonological store and the shifting of attention to move information in and out of this store. By manipulating normal subjects' ability to manipulate information in and out of the phonological loop, it was possible to produce frontal-like performance. Furthermore, it was possible to predict frontal-like performance in a patient with a deficit in phonological working memory. The results of these experiments not only indicate what components of the task are relevant to the production of the hallmark behavior of perseveration, but also help to explain why many other patients with no frontal deficits also display perseveration on the WCST: They may have working memory and or attentional deficits.

The attentional allocation experiments reported in this paper indicate that frontal patients do indeed have a deficit in the allocation of attention. When patients had to dynamically switch attention from one task to another, their ability to perform the appropriate task dropped to chance levels. This inability to dynamically allocate attention may be at the root of patients difficulties on the WCST and other tasks (e.g., planning, estimating etc.). In the case of the WCST, an inability to switch attention may mean that subjects do not update the feedback information in the phonological store, and perseveration then occurs. What this type of analysis indicates is that to truly understand the nature of frontal deficits we must go beyond simple task descriptions and discover the dynamic properties underlying complex tasks. As the results of the experiments reported here show, an analysis of the dynamics of a task help reveal the mechanisms underlying frontal deficits and how together these mechanisms make up higher-level cognition.

The results of the experiments go beyond merely concluding that the frontal lobes are concerned with attentional allocation and working memory. Specifically, this research suggests that the deficits in higher level reasoning observed in frontal patients occur when the task involves the maintenance of a temporary representation in working memory. we hypothesize that the Central Executive or attentional allocation system cannot update information in the temporary stores, particularly when there is more than one chunk of information to be maintained in working memory. The model presented here moves from a static account of how subjects and patients use information while reasoning to a dynamic account that stresses the importance of temporary representations used in higher level thinking. By conducting detailed task analyses of the changing representations that subjects and patients generate while performing a task, it is possible to predict frontal like deficits in normal subjects when they are prevented from constructing these temporary representations. The key to understanding frontal deficits is twofold; knowing what temporary representations are involved in a task and the operations that must be performed on these representations. Theories that are solely concerned with attentional or working memory deficits without regard to the mental operations and contents of temporary representations will only provide a partial picture of the cognitive deficits underlying frontal deficits in higher-level cognition.

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References

Table 1

	Control	Phonological	Executive	Milner	Heaton
Categories	6	2.3	4	1.8	3.1
Perseverative errors	5.2	40	26	44.6	35.9
Non-perseverative errors	14	27	27	15	18.4
Perseverative errors in first category	0.6	11.6	4.6		
Perseverative errors in second category	1.1	16	25		
Non-Perseverative errors in first category	2.3	10.1	8.0		
Non-Perseverative errors in second category	4	11	10		

Performance of normal subjects in the three experimental conditions and performance of frontal patients in Milner study and Heaton norms

	Articulatory suppression	Left Foot	Right Foot
Number of categories	4.3	4.9	3.9
Number of perseverative errors	29	16	19
Number of non-perseverative errors	23	24	24
Perseverative errors in first category	1.2	1.6	1.1
Perseverative errors in second category	19.7	6.4	18.4
Non-perseverative errors in first category	2.7	5.3	4.2
Non-perseverative errors in second category	6.5	7.1	11.6

Table 2: Experiment 2 performance for the three experimental conditions

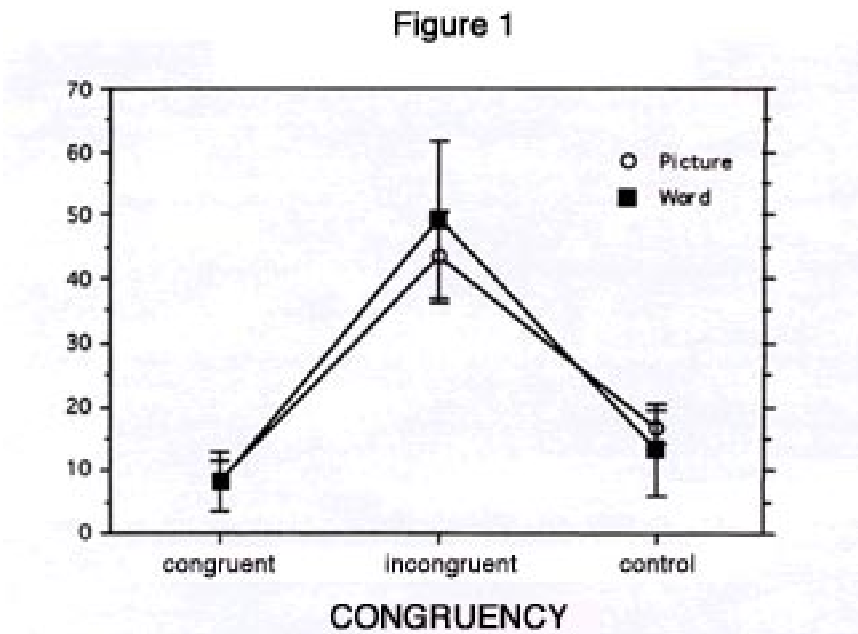
Incongruent Same set	Incongruent Different set	Control	Congruent
803	800	706	653

Table 3: Reaction time of subjects for the four conditions of the picture-naming task.

Figure 1

Figure 1

Percentage of errors for subjects in the task switching version of the picture-word interference task.



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