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Capacity limitations in short-term memory in schizophrenia: tests of competing hypotheses

T. E. GOLDBERG,[1] K. J. PATTERSON, Y. TAQQU AND K. WILDER

From the Clinical Brain Disorders Branch, Intramural Research Program, NIMH, Neuroscience Center at St Elizabeths, Washington, DC, USA

ABSTRACT

Background. Capacity limitation theories have proved to be surprisingly resilient in characterizing some of the cognitive deficits in schizophrenia. However, this perspective has not generally been applied to short-term verbal memory tasks. We explored this issue by first attempting to ascertain if gross misallocations of processing resources might explain impairments in short-term memory in schizophrenia on a classic digit span task and in a second study by attempting to determine what effects delay and memory set size had on a divided attention short-term verbal memory paradigm.

Methods. In the first study 16 patients with schizophrenia and 21 normal controls received 40 trials of a three digit task and 20 trials of a six digit span task. As the absolute number of digits presented and duration of presentation in two conditions were identical, subjects thus had equivalent 'opportunities' to make errors if distraction, in the sense of misallocation of cognitive resources, were at the root of poor performance. In the second study 15 patients with schizophrenia and 15 normal controls were tested in conditions in which two, four or six words were presented and in which rehearsal was prevented by an interference task (colour naming) for delays of 5, 10 or 15 s.

Results. Patients had disproportionate difficulty on the six digit rather than the three digit condition, suggesting that deficits in the verbal working memory short-term store may not be the result of attentional factors. In the second study, patients' performance was differentially worsened by the interference task, by memory set size (i.e. a capacity limitation) and by delay, a measure of decay rate.

Conclusions. In concert, these studies demonstrate that schizophrenia patients have difficulties on verbal short-term memory span tasks not because of misallocation of resources, but rather because of limitations in 'representational capacity' and maintenance of information over delays.

INTRODUCTION

Capacity limitation theories have proved surprisingly resilient in characterizing some of the cognitive deficits in schizophrenia (Granholm, 1992). These accounts have generally assumed that there are limited pools of information processing resources that are available at any given moment during the performance of a cognitive task. It has been suggested that there are several different possible causes of reduced resources in schizophrenia. These include a diminution in the total amount of resources, a deficit in the process of allocating of resources, and impairments in so-called automatic processing (which if dysfunctional would require the use of controlled resource demanding processes to carry out subtasks) (Gjerde, 1983; Granholm *et al.* 1996).

In the present set of studies, we wished to examine putative capacity limitations in a variety of short-term memory tasks. These types of tasks of have not come under scrutiny from a capacity limitation perspective. In the first study, we attempted to ascertain if gross misallocations

[1] Address for correspondence: Dr Terry E. Goldberg, NIMH Neuroscience Center at St Elizabeths, Washington, DC 20032, USA.

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of processing resources might explain impairments in short-term memory in schizophrenia on a classic 'digit span' task. In the second study, we attempted to ascertain what effects delay and representational load had on an experimental variant of a divided attention/dual task short-term memory paradigm, the so-called Brown–Peterson test (Brown, 1958; Peterson & Peterson, 1959). In this study, rather than manipulate features of the secondary task as we had done previously (Fleming *et al*. 1995), we attempted to manipulate features of the primary mnemonic task.

STUDY 1

Do digit span impairments in schizophrenia reflect attentional or short-term memory limitations?

Digit span tests of the type often involved in routine mental status testing have frequently been administered to patients with schizophrenia. The results, however, have been conflicting. Park & Holzman (1992) reported that digit span was intact in patients with schizophrenia, as did Kolb & Whishaw (1983) and Tamlyn *et al*. (1992). Goldberg *et al*. (1993) reported that forward digit span was intact. In these studies, the maximum span attained prior to two consecutive incorrect responses was used as the dependent measure. In contrast studies that have examined the number of correct responses made to a list of digit span trials have generally found that patients perform below the normal level (Goldberg *et al*. 1997).

The cognitive underpinnings of digit span have received surprisingly little attention considering its widespread clinical use. One account that has gained relative currency involves concepts associated with verbal working memory. In particular, it is thought that a subvocal articulatory rehearsal mechanism is used to maintain information while a phonological store encodes acoustic information (Baddeley, 1986). The absolute amount of information that can be maintained in this store is thought to be about seven units of information in the absence of specialized 'chunking' strategies (Miller, 1956). To our knowledge no investigator has proposed the presence of frank limitations in verbal short-term working memory in schizophrenia.

A second account of digit span involves attentional dysfunction or more accurately, distraction (used here in the conventional sense of an inappropriate allocation or diversion of cognitive resources to extraneous internal or external stimuli). In studies of selective attention investigators consistently found that patients with schizophrenia had differential difficulty in responding to digit sequences while ignoring a secondary distracting voice (Oltmanns & Neale, 1975; Harvey & Pedley, 1989; Corrigan & Green, 1991). However, even the performance on a list of neutral digit span trials (i.e. without distraction) was worse in patients. On the basis of a factor analysis of a large group of normal subjects Mirsky (1987) suggested that digit span reflected an 'encoding' attentional function. Kremen *et al*. (1992) came to a similar conclusion using a schizophrenic sample. The 'attentional' scale of the Wechsler Memory Scale Revised includes digit span and is generally deficient in schizophrenia (Gold *et al*. 1992*a*), consistent with the notion that digit span measures attention. Weiss *et al*. (1988) observed that patients appeared to suffer from 'overload' as they recalled fewer than three items of seven digit sequences more than 30% of the time, while no normal subjects displayed this pattern of performance. Results were attributed to defective filtering and subsequent volitional 'disattention'.

The primary objective of the present study was to determine if susceptibility to distraction provides an adequate explanation for poor digit span performance. Secondly, we sought to understand the effects of difficulty level on schizophrenic performance.

Method

Subjects

Sixteen patients with schizophrenia and 21 normal subjects comprised the sample. The mean age and education of the schizophrenic group were 33·4 + 7·8 and 12·4 + 1·4 years respectively; mean age and education of the normal group was 24·3 + 6·9 years and 16·6 + 1·8 years respectively. Mean estimated pre-morbid intellectual levels (based on WRAT Reading Standard Scores) were 98·2 + 15·3 for the schizophrenic group, and 112·7 + 7·9 for the normal group.

All patients were hospitalized at the NIMH Neuroscience Research Hospital at St

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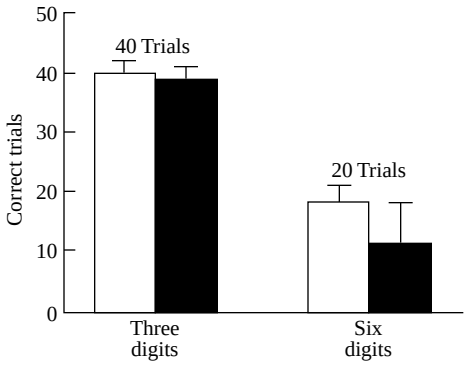


FIG. 1. Number of correct three digit and six digit trials by schizophrenic (■) and normal (□) subjects.

Elizabeths, a tertiary care research facility. All patients received DSM-III-R diagnoses of undifferentiated or paranoid schizophrenia as determined by SCID. Mean duration of illness was 13·8 + 10·2 years. No patient had a current diagnosable neurological disorder or a substance abuse disorder. All schizophrenic patients were receiving neuroleptic medications at the time of the study. The medication regimens included clozapine ($N = 5$), risperidone ($N = 2$), and high potency typical neuroleptics ($N = 9$). Five patients also received adjunctive medication, most commonly benztropine. The normal group was screened for the presence of psychiatric history, depressive or psychotic symptoms, and illicit substance or alcohol abuse, as well as the presence of neurological diseases, including head injury, cerebrovascular accidents, and CNS infection.

Procedure and tests

All subjects received the following orally presented digit span tests in the order listed below. Items were scored as correct or incorrect (i.e. partial scores were not utilized) insofar as all numbers of a given trial were recalled in appropriate sequence without deletions or additions.

1 *Three digits forward* Subjects were requested to repeat three digits presented at the rate of one per second in the order presented. Forty trials were administered.

2 *Six digits forward* Subjects were requested to repeat six digits presented at the rate of one per second in the order presented. Twenty trials were administered.

Table 1. *Repeated measures analysis of digit span data in controls and schizophrenia*

	F	*P*
Dx (1, 35)	31·98	0·0001
Presentation (1, 35)	78·80	0·0001
Presentation × Dx (1, 35)	10·08	0·003
Span (1, 35)	167·86	0·0001
Span × Dx (1, 35)	13·04	0·0009
Presentation × Span (1, 35)	11·79	0·002
Presentation × Span × Dx (1, 35)	0·06	0·81

3 *Three digits backward* Subjects were requested to repeat three digits presented at the rate of one per second in reverse of the order presented. Twenty trials were administered.

4 *Six digits backward* Subjects were requested to repeat six digits presented at the rate of one per second in reverse of the order presented. Ten trials were administered.

Results and discussion

Mean raw digit span scores for all conditions are illustrated in Fig. 1. If attention were a critical determinant of performance in schizophrenia then performance should be equivalent irrespective of number of digits, as attentional interruption should exact an equal cost irrespective of condition. Because the absolute number of digits presented and duration of presentation in the two conditions were identical in the present paradigm, subjects had equivalent 'opportunities' to make errors. We first examined this pattern of performance in multivariate repeated measures analysis of variance in which all three digits span tasks were compared to all six digits span tasks (forward, backward). Results are listed in Table 1. A significant diagnostic group difference was observed, as was a span length difference. Crucially, a group × span interaction was also found. Patients had disproportionate difficulty on the six digits conditions. In addition to these results a main effect for type of presentation (forward or backward) was also found, suggesting that the processing demands of the backwards condition were greater. A presentation type × group interaction was present, suggesting that the processing demands of the backward condition had a disproportionate influence on schizophrenic performance. A type × span × group interaction was not present.

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Illustrative of the results were matched pair difference scores in the normal and schizophrenic groups in the three and six digits forward conditions. Normal subjects attained 100% and nearly 90% correct respectively. Patients attained about 98% correct on the three digits forward test while only 60% correct on the six digits forward test. When the magnitude of the differences was compared between the groups, a significant difference was observed by matched pair t test ($t = 5{\cdot}08$, $P = 0{\cdot}0001$). The difference between the span tasks in the schizophrenia group was larger, suggesting that results were due to structural and/or processing limitations in short-term memory, rather than attentional deficiencies. Moreover, when a measure of premorbid intellectual function (WRAT-R Reading) was utilized as a covariate, the contrast between the two groups on the difference score measure still approached significance ($P = 0{\cdot}07$).

In summary, patients with schizophrenia performed poorly on digit span sequences of six items compared to normal subjects. These results indicate that patients do indeed have impairments on this task, consistent with some, but not all earlier investigations. Moreover, these results probably cannot be attributed to simple attentional failure in the sense of gross dysfunction in the allocation of cognitive resources to extraneous external or internal stimuli as schizophrenic patients had more difficulty on the six than on the three digit condition, though the actual number of digits and duration of presentation was equivalent in the conditions.

In a systematic investigation of the verbal working memory 'slave system', Fleming *et al.* (unpublished) found that patients performed more poorly irrespective of experimental manipulation, including word length and phonological similarity, and without evidence for a task × diagnosis interaction. This also suggests the presence of capacity limitations, rather than qualitative abnormalities. While remembering six digits may be subjectively experienced as more attentionally demanding, this may be an epiphenomenon of capacity limitations (in normal or schizophrenic individuals). That is, attentional failure may be experienced subjectively by the subject when capacity is exceeded, but it is a result, not a cause, of digit span failure. Our results do not address whether patients do poorly or even differentially poorly on tests of selective attention; rather they suggest that a fundamental deficit in short-term memory may coexist with such a tendency.

There are caveats to this experiment so the results should be interpreted cautiously. It is possible that the findings are due to more frequent orientating cues in the three rather than six digit condition, which result in greater arousal. However, the literature on arousal in schizophrenia does not support this, as there are thought to be subgroups of patients not only hypo-aroused, but also hyper-aroused or normo-aroused (Dawson & Nuechterlein, 1984; Kring & Neale, 1996). It is also unclear if the findings are due to the amount of information which must be maintained or the duration over which stimuli must be maintained (though both may be considered aspects of cognitive load or capacity, as in Cohen *et al.* 1997). This will be investigated in more detail in the next study.

STUDY 2

What accounts for poor performance by schizophrenia patients on the Brown–Peterson task: delay or representational space?

Brown (1958) and Peterson & Peterson (1959) found that three items could be lost from memory over intervals of < 20 s if subjects were prevented from subvocally rehearsing the material by performance of a secondary task. Recent models of the Brown–Peterson task and short-term or working memory have emphasized the limited capacity of the module necessary to implement the task (Shallice, 1988). The interpolated distracter task, especially if difficult, is thought to draw resources from the limited capacity pool of a central executive, decreasing resources that would otherwise be allocated to 'maintenance rehearsal' or to the overall coordination of the task.

Among normal subjects, semiautomatic tasks that do not draw on verbal processing resources, such as finger tapping or simple semiautomatic verbal articulation tasks, do not cause a decrement in Brown–Peterson performance. In schizophrenia, however, the situation is more complex. Fleming *et al.* (1995) found that simple counting led to a marked decline in performance of schizophrenic patients. This result suggested that patients rely markedly on an active articulatory rehearsal process. When this process is

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disrupted, the maintenance rehearsal function of the 'central executive' cannot mediate the task. Because schizophrenic patients did not display decrements in performance during the distractor task consisting of tapping, impairments did not appear to be due to resource allocation *per se*. A number of previous studies have also generally indicated that patients with schizophrenia performed at levels lower than normal subjects when verbal distractors were utilized (Weinberger & Cermak, 1973; Stuss *et al*. 1982; Randolph *et al*. 1992).

No study to date has systematically manipulated memory load or set size on working memory in the Brown–Peterson paradigm (i.e. the number of items to be remembered) and only one study has systematically manipulated delay. The purpose of the present study was to investigate the effects of both memory set size and delay on recall in order both to infer the amount of representational space available and the ability to maintain information temporally. We varied set size by requesting that subjects remember either two, four, or six words. We varied delay by requesting that subjects remember material over a 5, 10, or 15 s delay. (Interference involved colour naming.) We used a control task that did not involve an interference condition to assess reliance on covert rehearsal strategies.

Method

Subjects

The sample consisted of 15 patients with schizophrenia and 15 normal controls. The schizophrenia volunteers met the DSM-IV criteria for schizophrenia and were in-patients at the National Institute of Mental Health, Washington, DC, USA. Five of the patients were receiving clozapine and four of the patients were receiving risperidone at the time of testing. The remainder of the patients were on a variety of typical neuroleptics. Ten of the patients were also receiving adjunctive medications, most frequently benztropine. The patients were all screened to ensure clinical stability before testing began. The schizophrenic group was comprised of 13 males and two females. Normal controls were recruited for participation, none of whom reported a previous diagnosis of mental illness, neurologic disease or insult, or substance abuse. The normal group consisted of nine males and six females. Mean age was 34·4 + 8·9 for the schizophrenia group and 33·0 + 11.9 for the normal group. The mean estimated pre-morbid IQ for patients was 105·7 + 15·3 compared with a score of 111·4 + 15·0 for normals as measured by the WRAT-R.

Brown–Peterson task

To assess the effects of delay and memory set size on the working-memory system, both groups of subjects were tested in each of the conditions (2, 4, or 6 words per presentation, intervals of 5, 10, or 15 s, with and without interference) three times. For each condition the number of words correctly recalled over the three trials was summed to arrive at a score. Words were selected from the Toronto Word Pool (Friendly *et al*. 1982) on the basis of low imagery ($< 4{\cdot}2$) and high frequency (> 10).

The subject was shown a card on which 2, 4, or 6 words were written in bold print and asked to read the words aloud. The experimenter then withdrew the card. At the end of a timed interval (5, 10, or 15 s) the subject was asked to recall the words he/she had read previously. Before each trial the experimenter indicated whether the subject was to engage in an interference task (which consisted of rapidly naming colours – red, blue, or green – from a template organized in columns) during the delay. The purpose of the colour naming task was to disrupt subvocal rehearsal. Trials were presented in fixed, randomized order.

Results and discussion

Performances (in raw scores) of the control and schizophrenic groups are illustrated in Fig. 2*a*–2*c*. Statistical analysis using a repeated measures MANOVA was applied to log-transformed data in order to normalize the positively skewed distribution of the schizophrenia patients. Diagnostic group was a between subjects factor with two levels (schizophrenia, normal); delay (three levels: 5, 10, 15 s), set size (three levels: 2, 4, 6 words); and distractor (two levels; present, absent) were within subject factors. Results are listed in Table 2. A main effect for group was present; patients with schizophrenia performed consistently more poorly across conditions than normal controls. A main effect for delay was present, as was a group × delay interaction, suggesting that the

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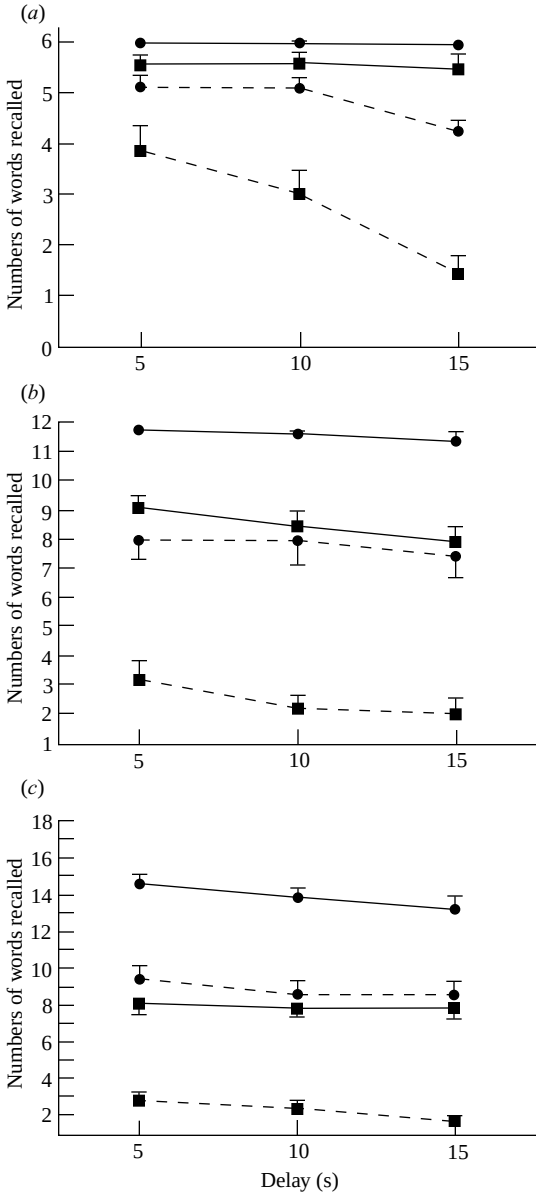


FIG. 2. Performance means (+SEM) of schizophrenic patients (– – –) and normal controls (—) across delays of 5, 10, or 15 s with (■ BP) or without (● CTRL) interference task (colour naming) for a memory set size of Brown–Peterson task: (*a*) two words; (*b*) four words; and (*c*) six words. Untransformed raw scores are used in these graphs.

schizophrenic patients were differentially effected by delays of $\geqslant 5$ s. A main effect for interference (present/absent) was present, in keeping with the literature. A significant group × interference condition was present: schizophrenic patients' performances were differentially effected (worsened) by the interference (colour naming). This suggests that schizophrenic patients rely to a greater extent than do normals on covert articulatory rehearsal mechanisms. When these are disrupted (by the distractor) performance precipitously decreased, suggesting that alternative mechanisms for short-term recall were absent or inaccessible. A significant main effect for memory set size was found (subjects remembered more words from the larger memory sets). Importantly, a group × memory set size interaction was present, as schizophrenia patients performance was differentially worse in comparison to normal controls in conditions with larger sets (e.g. six words). This finding suggests that schizophrenic patients have capacity limitations in their representational space. Indeed, in interference conditions schizophrenia patients never recalled more then three words, irrespective of set size.

No delay × set size, delay × distractor × group, delay × set size × group, or distractor × set size × group interactions were present. A distractor × set size interaction was present; interference when present exacted its largest cost when set size was greatest. A distractor × delay interaction was present as well; this suggests a more rapid decline in memory when rehearsal was prevented. Interestingly, a lack of interaction between delay and set size suggests that these two variables may be independent or dissociable aspects of 'capacity'.

Table 2. *Brown–Peterson repeated measures MANOVA results*

	F	*P*
Dx (1, 27)	42·72	0·0001
Delay (2, 54)	17·41	0·0001
Delay × Dx (2, 54)	4·87	0·02
Interference (1, 27)	140·32	0·0001
Interference × Dx (1, 27)	32·39	0·0001
Set size (2, 54)	34·21	0·0001
Set size × Dx (2, 54)	23·06	0·0001
Delay × Interference (2, 54)	4·29	0·03
Delay × Interference × Dx (2, 54)	1·72	0·20
Delay × Set size (4, 108)	1·08	0·39
Delay × Set size × Dx (4, 108)	0·14	0·97
Interference × Set size (2, 54)	11·57	0·0003
Interference × Set size × Dx (2, 54)	1·20	0·32
Delay × Interference × Set size (4, 108)	2·01	0·13
Delay × Interference × Set size × Dx (4, 108)	1·14	0·36

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Our results suggest that patients with schizophrenia exhibit reduced capacity for representing verbal material in a short-term memory store. In particular, it appeared that the presence of a distractor that prevented rehearsal, longer delays, and a large set size all had disproportionate impact on schizophrenic performance. While we had did not utilize a no-delay condition, results from the prior study of digit span offer a surrogate no-delay condition. At reduced set size (i.e. three digits) and performance of schizophrenia patients was adequate, but at a larger set size (six digits) performance was impaired. Again this is consistent with an account that emphasizes capacity and not consistent with efficiency or attentional accounts. In addition, patients relied on covert rehearsal more so than did normals. When covert rehearsal was disrupted with a distractor task, patients performance was markedly diminished. This is clearly illustrated in Fig. 2. This latter finding suggests by implication a dysfunctional or exceedingly limited central executive, the cognitive module presumed to be responsible for maintenance rehearsal in the absence of slave system components (articulatory rehearsal) or for indexing or pointing towards the storage location of the material. Reliance on covert rehearsal also suggests that schizophrenia patients were neither passive in their information processing strategies nor lacking in motivation. Moreover, under no Brown–Peterson condition were schizophrenia patients able to recall on average more than three words per trial. This measurement may rather directly reflect central executive capacity.

GENERAL DISCUSSION

The studies reported here demonstrate that schizophrenia patients have difficulties on short-term verbal span tasks not because of misallocation of resources, but because of limitations in capacity. Patients' failure on such tasks was not due to lack of rehearsal. When rehearsal was interrupted or processing demands made more difficult, performance worsened differentially in the schizophrenic group. Both demands on representational space (memory set size) and information maintenance over delays had impact on the performance of schizophrenia patients. *In toto*, these results provide further evidence for the presence of storage and certain types of processing limitations in schizophrenia.

Difficulty patterns may also be subject to explanations based on capacity limitations. It is easily appreciated that the digits backward tasks are more difficult than the forward tasks and hence may be more sensitive to dysfunction. Our results suggest that when the demands for transformation of information are made that are different from the veridical reproduction of information, more cognitive resources are required. Perhaps these reside in the so called central executive.

Results from the Brown–Peterson task are consistent with this view in that performance of patients declined steeply when simple covert rehearsal was prevented. By process of elimination some other apparatus in the cognitive system, one often thought to reflect a central strategic reserve resource supply and which is involved in maintenance rehearsal, may be considered to be impaired, perhaps differentially so. In a previous study of a Brown–Peterson task (Fleming *et al.* 1995) we had shown that impairments were not due to general problems in resource allocation, as only those interference tasks that directly interrupted rehearsal resulted in a decline in performance in the schizophrenia group. We have now replicated and extended these findings. First, we have shown in the present study that patients were exceptionally sensitive to an interference condition (which interrupted rehearsal). Secondly, we have now shown that set size and delay appear to be critical factors in determining performance of patients.

The neurophysiological concomitants of such limitations may be worth commenting upon. We have recently found, based on ^{15}[O]-water rCBF PET measurements, that information overload produces qualitative decreases in regional brain activity in prefrontal cortex in normal subjects (Goldberg *et al.* 1998). These decreases corresponded to performance decrements that we also observed in a dual task paradigm that served as an activation condition during the PET scan.

The issue of medication must also be addressed. Typical neuroleptics and benztropine have been shown to have little effect on working memory tasks (Saykin *et al.* 1994; Goldberg & Weinberger, 1996). Clozapine may have an adverse effect (Goldberg & Weinberger, 1996)

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but it should be noted that: (1) only a minority of patients were receiving the latter drug; and (2) the adverse impact is occurring in a system whose function is already demonstrably compromised.

To conclude, it appears that we and perhaps other investigators have been facile in viewing digit span recall deficits as failures in concentration. The present study is instructive in this regard, because it indicates that digit span impairments are not due to global difficulties in vigilance or concentration, i.e. resource allocation, but rather limitations in short-term memory capacity. The results of this study may convey a broader message as well. The concept of a monolithic attentional impairment in schizophrenia has been found to have curiously limited explanatory power because it does not account for the plethora of cognitive impairments frequently found in these patients (Kenney & Meltzer, 1991). Moreover, classic tests of attention, including the CPT, may not test attention *per se*, but rather working memory or a form of response preparation (Goldberg & Weinberger, 1995; Servan Schreiber *et al*. 1996). Even in paradigms that measure distinct types of attentional processes, findings have been task specific and qualitative deficits difficult to discern, as for example in a cued spatial attention task (Gold *et al*. 1992*b*). Thus, unitary models of attention may not be of value in understanding the cognitive pathology of schizophrenia. It may be more heuristic to view information processing as dependent both upon multiple pools of resources dedicated to computationally specific modules. In schizophrenia the size of such pools may be reduced.

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