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Schizophrenia Research 63 (2003) 201–217
SCHIZOPHRENIA RESEARCH
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Wisconsin Card Sorting Test performance in schizophrenia: the role of working memory

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Received 25 January 2002; received in revised form 25 June 2002; accepted 28 June 2002

Abstract

Schizophrenia typically results in reduced performance on the Wisconsin Card Sorting Test (WCST). In the current study, we used a variety of approaches to examine the role of working memory (WM) in this deficit. One approach was to examine patterns of perseverative and non-perseverative errors. A second approach involved the comparison of the standard WCST to a modified version that used visual cues to reduce demands on WM. A third approach was to quantify the impact of WM demands on performance on a trial by trial basis. Consistent with theories of WM, the schizophrenia group showed increases in both perseverative and non-perseverative errors and differences between individuals with schizophrenia and controls were largest when WM demands were high. The visual cues helped the schizophrenia group overcome the high WM demands of the test, although they did not reduce the impairment in terms of standard scoring procedures. All impairments disappeared, however, after controlling for group differences on a measure of the speed of encoding information in WM. The pattern of results supports the conclusion that WM impairment contributes to poor performance on the WCST in individuals with schizophrenia, with additional evidence that this impairment results from generalized slowing of information processing.

Keywords: Schizophrenia; Wisconsin Card Sorting Test; Working memory; Slowing; Cognition

1. Introduction

The Wisconsin Card Sorting Test (WCST) has been widely used in research with schizophrenia, and deficits in this population are well documented (Heaton et al., 1993; Koren et al., 1998; Van der Does and Van den Bosch, 1992). The nature of the cognitive impairment on this test has not been fully established, however. The current study focuses on the hypothesis that deficits in working memory (WM) contribute to the impairment.

WM refers to the limited capacity system for temporary storage and processing of information (Baddeley, 1986) that is known to depend on the integrity of the prefrontal cortex (Goldman-Rakic,

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doi:10.1016/S0920-9964(02)00353-5

1987; Cabeza and Nyberg, 2000). The fact that individuals with schizophrenia have prefrontal cortex dysfunction and that their poor WCST performance is associated with reduced activity in this part of the brain (Berman et al., 1986; Seidman et al., 1994; Weinberger et al., 1986) lends credence to the hypothesis that impaired WM contributes to their poor performance on the WCST. From a cognitive perspective, performance on the WCST is thought to rely on WM because it requires individuals to concurrently store and utilize information from completed sorts while processing information on each new card as it is presented (Berman et al., 1995; Cohen and O'Reilly, 1995; Dehaene and Changeux, 1991; Kimberg and Farah, 1993).

Reduced WM ability in schizophrenia is already well established using a wide range of tests (see Keefe, 2000 for a review). Such deficits have been demonstrated on complex tasks such as the Letter–Number Sequencing Test (Gold et al., 1997), the N-Back task (Carter et al., 1998; Huguelet et al., 2000), random generation of digits and letters (Artiges et al., 2000; Salamé et al., 1998), and complex sentence and computation span tasks (Condray et al., 1996; Morice and Delahunty, 1996; Stone et al., 1998), as well as on simple tests of span for locations, colors, objects, and digits (e.g., Heinrichs and Zakzanis, 1998; Salamé et al., 1998; Spindler et al., 1997). A number of recent investigations have shown similar deficits on Delayed Response (DR) and Delayed Match to Sample (DMTS) tasks (Carter et al., 1996; Fleming et al., 1997; Hartman et al., in press; Javitt et al., 1997; Keefe et al., 1995; McDowell and Clementz, 1996; Park and Holzman, 1992, 1993; Park et al., 1999; Snitz et al., 1999; Stratta et al., 1999).

A number of studies have also confirmed a relationship between impairments in WCST and WM performance in schizophrenia. Significant correlations have been found between the WCST and DR/DMTS tasks (Keefe et al., 1995; Park, 1997; Seidman et al., 1994; Snitz et al., 1999), sentence span tasks (Morice and Delahunty, 1996), the Letter–Number Sequencing Test (Gold et al., 1997), the N-Back task (Huguelet et al., 2000), and an abstraction task with delays (Glahn et al., 1999) (see Stratta et al., 1997, for an exception). Furthermore, these correlations remain significant even after partialing out the contribution of generalized cognitive dysfunction and lower IQ (Snitz et al., 1999; Gold et al., 1997). Additional support for the contribution of WM to reduced WCST performance comes from evidence that statistical control of performance on WM tests eliminates the differences between schizophrenia and control groups on the WCST (Glahn et al., 1999; Gold et al., 1997).

In sum, the existing literature provides substantial evidence for a relationship between schizophrenia, WM deficits, and WCST performance. Nevertheless, all the studies to date have been correlational in nature, and none have examined the pattern of performance on the WCST to determine how a deficit in WM actually impacts performance. The premise of the current study is that WM deficits in individuals with schizophrenia should lead to patterns of performance on the WCST that differ from those of healthy individuals. Thus, we hoped to provide a direct test of the hypothesis that reduced WM function contributes to impairments on the WCST.

The framework we used to investigate this question rests on the expectation that failures of the WM system result in diminished ability to encode and process information on-line, which in turn leads to errors. Furthermore, the majority of errors should be perseverative, because the most recent sorting rule is most salient in WM and therefore most likely to bias decision-making. If WM is severely impaired and the quality of available information greatly reduced, the tendency to produce perseverative errors may even increase disproportionately. Note that in this conceptualization, perseverative errors occur as a result of poor WM rather than from a primary deficit in cognitive inflexibility.

This conceptualization of the role of WM on the WCST is derived from computer simulations and from experimental studies of healthy adults. For instance, computer simulations have demonstrated that WM deficits produce both perseverative and non-perseverative errors (Dehaene and Changeux, 1991; Kimberg and Farah, 1993), with the ratio of perseverative to non-perseverative errors increasing with greater damage to WM (Kimberg and Farah, 1993). An overall increase in errors resulting from WM failure is also consistent with an early study with healthy young adults by Grant and Berg (1948), which we have replicated and extended in our laboratory (Hartman, unpublished data). Results of these studies have demonstrated that the ability to shift to a new rule is positively associated with the degree to which the old rule is learned: the more correct sorts required before the category shifts, the fewer errors are made. Perseverative and non-perseverative errors are similarly affected. Thus, errors decrease under conditions producing better WM for the rule.

Although these results suggest that WM functioning plays an important role in performance on the WCST, other data indicate that perseverative errors can also result from an independent deficit in cognitive flexibility. For example, patients with frontal lobe lesions, whose behavior often demonstrates reduced inhibitory function and inflexibility, show significant increases in perseverative errors on the WCST with smaller and generally non-significant increases in non-perseverative errors (Drewe, 1974; Heaton et al., 1993; Milner, 1963; Nelson, 1976). The proportion of perseverative errors increases with the severity of deficit (Berdia and Metz, 1998; Berman et al. 1986; Daneluuzo et al., 1998; Saoud et al., 1998; Sullivan et al., 1993). Thus, a relatively greater increase in perseverative versus non-perseverative errors may occur either when impairments in WM are severe or in the presence of significant cognitive inflexibility. When inflexibility is the primary cause of WCST impairment, however, there may be no increase in non-perseverative errors.

Taken together, the existing literature suggests that WM dysfunction in schizophrenia will produce specific patterns of errors on the WCST. We tested this hypothesis from a number of perspectives. First, we examined the pattern of perseverative and non-perseverative errors. Second, we introduced a modified version of the test that reduced the WM demands, and compared group differences on the standard and modified versions. Third, we developed a new scoring system for assessing the relationship between WM demands and errors on the test. Finally, we explored the possibility that slowed encoding into WM may account for impairment on the WCST.

The first approach focused on the pattern of perseverative and non-perseverative errors made by individuals with schizophrenia. Because schizophrenia results in lowered WM ability, we predicted an overall increase in errors compared to a control group, with more perseverative than non-perseverative errors for both groups. If impairments in WM are severe or if individuals with schizophrenia show cognitive inflexibility, then individuals with schizophrenia may also show a greater increase in perseverative than non-perseverative errors compared to healthy individuals. These predictions have not previously been tested, despite the large number of studies of WCST in schizophrenia. Whereas previous studies have documented an increased number of perseverative errors in individuals with schizophrenia, few have reported non-perseverative error scores, and none have compared the two types of errors. Those that have reported non-perseverative errors, however, have shown increases in schizophrenia (Franke et al., 1992; Snitz et al., 1999). In addition, although a number of studies have reported increases in the percentage of total sorts that involve perseverative errors (Berdia and Metz, 1998; Berman et al., 1986; Daneluuzo et al., 1998; Gold et al., 1997; Huguelet et al., 2000; Saoud et al., 1998; Sullivan et al., 1993), the percentage score is an imperfect measure of the frequency of perseverative responding, because higher scores could reflect either an increase in perseverative responses or an overall increase in all errors.[1]

A second approach to studying the role of WM in the impairments of individuals with schizophrenia on the WCST involved creating a version of the test with reduced WM demands. To the extent that WM deficits contribute to poor performance, our modifications to the test were expected to reduce the impairment. The modified version of the test reduced the demand on WM by introducing visual cues that provided information about the identity and outcome of the immediately preceding sort. The cues consisted of two cardboard arrows, one with the word 'YES' and the other with the word 'NO' on it. Each time verbal feedback was given, the examiner placed the appropriate arrow so that it pointed to the most recent sort; the arrow then remained visible during the sorting of the following card. We anticipated that these cues

[1] To give a hypothetical example: If a healthy individual produced 60 correct non-perseverative sorts, 10 perseverative errors and 10 non-perseverative errors, the percentage of perseverative responses would be 12.5%. If an individual with schizophrenia produced the same number of correct non-perseverative sorts, but more perseverative and non-perseverative errors (e.g., 20 of each), the percentage score would be 20%. Thus, the percentage of perseverative responses may be increased even when there are equivalent increases in both types of errors.

would reduce errors by providing an external source of information about the most recent sort and by facilitating encoding of information into WM. We predicted that the cues would benefit individuals with schizophrenia more than control participants.

A third approach to examining the role of WM in WCST impairments involved the development of a new scoring method. This new system was based on the idea that WM demands vary during the test both in terms of the amount of stored information needed to determine the current sorting rule and the amount of on-line processing required in order to reach the correct decision. In terms of storage, it is always necessary for the test-taker to remember the most recent sort, but demands on WM storage increase whenever multiple prior sorts are relevant to determining the correct rule. Similarly, processing demands are minimal when applying the rule used on the most recent sort to the subsequent card; however, if the most recent sort is incorrect, additional executive control processes are needed to inhibit the incorrect sorting rule while simultaneously holding in mind and evaluating other possible rules. Because higher storage and processing demands occur without the benefit of external cues, they both place an increased burden on WM resources.

The new scoring system examined the storage and processing demands at each point in the test where an error occurred. We expected that errors would be more frequent when demands are high. In addition, differences between participants with schizophrenia and controls should be largest at points in the test when WM demands are high and smallest when they are low. In the modified version of the WCST, because the cues were expected to reduce dependence on WM, we predicted that the effects of WM demands and group differences in these effects would also be reduced.

The final goal of the current study was to test the hypothesis that slowed WM encoding contributes to impairments on the WCST. In order to do this, we focused on a subset of the current sample who also participated in a study using a computerized version of the DMTS task (Hartman et al., in press). For these individuals, we examined the relationship between WCST scores and speed of WM encoding. On the DMTS task, the test-taker is required to encode new information on each trial and maintain that information over a distraction-filled delay period. Results of the DMTS study showed that when there was a limited amount of time to encode information, individuals with schizophrenia had significant deficits in WM. However, these deficits disappeared if study times were calibrated to produce equivalent performance under 0-delay conditions for the schizophrenia and control groups. These findings suggested that individuals with schizophrenia are slow to encode information into WM. Therefore, if inefficient encoding contributes to reduced performance on the WCST, we would expect significant correlations between speed of encoding on the DMTS task and WCST scores, and statistically controlling for DMTS performance should reduce group differences on the WCST.

To summarize, the goal of the current study was to evaluate the role of WM in impairments among individuals with schizophrenia on the WCST. Although successful performance on the WCST requires cognitive skills in addition to WM, such as attention, concept formation, reasoning, and decision-making, reduced WM can be expected to produce a predictable pattern in terms of the types of errors, the effects of memory cues, and the relationship of WCST performance to a measure of WM encoding speed. Results of this study should provide evidence of the extent to which WM deficits explain WCST impairment among individuals with schizophrenia.

2. Methods

2.1. Participants

Participants included individuals with confirmed schizophrenia and a matched healthy control group. All participants had English as their first language.

2.1.1. Participants with schizophrenia

Participants with schizophrenia included outpatients at the University of North Carolina Neuroscience Hospital in Chapel Hill, NC, and at Dorothea Dix Hospital, a state psychiatric facility in Raleigh, NC, as well as inpatients at John Umstead Hospital, a state psychiatric facility in Butner, NC. They included 28 individuals (4 women and 24 men; 16 inpatients and 12 outpatients) with a mean age of

31.7 years (SD = 10.4, range = 18–53) and an average of 12.9 years of education (SD = 2.4, range = 9–18 years). All were initially diagnosed with schizophrenia by the attending psychiatrist, and met DSM-IV (American Psychiatric Association, 1994) criteria for schizophrenia, based on chart review and diagnostic interview using the Structured Clinical Interview for DSM-IV Axis I Disorders-Patient Version (SCID-I/P, Version 2.0; First et al., 1996). All diagnostic interviews were conducted by individuals formally trained to use the SCID-I/P. Diagnoses included paranoid ($N = 14$), undifferentiated ($N = 10$), and disorganized ($N = 4$) subtypes of schizophrenia.

Participants were excluded for any significant past or present central nervous system disorders (e.g., seizure disorder, cerebral vascular disease), traumatic brain injury, loss of consciousness for 10 min or longer, learning disability, attention deficit/hyperactivity disorders, multiple repeated grades, mental retardation, or dementia. Participants were also excluded if they had a history of behavioral or conduct problems that were not consistent with schizophrenia.

Additional exclusion criteria involved alcohol and other substance use. Those meeting DSM-IV criteria for either current or lifetime alcohol or polysubstance dependence were eliminated from the study. Lifetime abuse/dependence was defined as (1) a period of dependence or abuse lasting 1 year or longer, or (2) more than three episodes of alcohol dependence lasting longer than 6 months within a 5-year period. Other criteria for exclusion included a reported pattern of drinking more than two alcoholic drinks in a 24-h period on three or more days per week. Use of injection drugs, PCP, Ecstasy, or other synthetic agents more than twice over the lifetime was also a criterion for exclusion. Chart review, interviews, and information from area mental health programs that was available in the course of treatment planning revealed that no participants had documented use of illicit substances for at least 3 months prior to testing and that three reported no history of any use.

Screening was also used to rule out significant hearing and vision impairment as well as color blindness. In addition, none of the participants had used cold or allergy medications within 72 h prior to testing. Finally, any potential participant who had participated in a medication study and/or used experimental psychiatric medications in the last 6 months was removed from the initial participant pool.

All participants except two were receiving psychopharmacological treatment at the time of the study. Eleven were taking neuroleptic antipsychotic agents [haloperidol ($N = 6$), fluphenazine ($N = 4$), thiothixene ($N = 1$)], while 15 were being treated with atypical anti-psychotic medication [clozapine ($N = 4$), olanzapine ($N = 5$), risperidal ($N = 5$), quetiapine ($N = 1$)]. Other medications included lithium ($N = 1$), fluoxetine ($N = 3$), valproic acid ($N = 3$), trihexyphenidyl ($N = 1$), and benztropine ($N = 3$).

The age of onset of schizophrenic symptoms had a mean of 21.7 years (SD = 5.4, range = 14–38), and the average duration of illness was 9.4 years (SD = 10.1 years, range = 1–32). Participants had been hospitalized an average of 3.7 times (SD = 2.1, range = 1–8).

2.1.2. Control participants

The 28 participants (4 women and 24 men) who comprised the control group were recruited from the surrounding community and were paid for their participation. They had a mean age of 29.9 years (SD = 9.0, range = 19–48) and an average of 12.7 years of education (SD = 3.8, range = 1–20 years). All were screened for lifetime episodes of affective, substance use and all psychotic disorders using the Structured Clinical Interview for DSM-IV Axis I Disorders-Non-Patient Version (SCID-NP, Version 2.0; First et al., 1996). Exclusion criteria included the same general and medical criteria as for the participants with schizophrenia. Exclusion criteria for alcohol use in controls were as follows: (1) heavy drinking or problems controlling alcohol intake in the past 6 months, (2) drinking four or more days per week in the past month, (3) drinking seven or more drinks in a 24-h period in the last month, or (4) intoxication four or more days in the last month. Use of injection drugs, PCP, Ecstasy, or other synthetic agents more than twice over the lifetime was also a criterion for exclusion.

2.2. Tasks

2.2.1. Wisconsin Card Sorting Test (WCST; Heaton et al., 1993)

Participants performed the WCST under two conditions: the standard administration and one with modifications. One deck of 64 cards was used for each condition. For the standard administration of this test, test-takers sort a deck of cards into four piles, each marked by a key card. Each card has one to four designs on it that appear in one of four different colors (red, green, yellow, or blue) and in one of four shapes or 'forms' (triangles, crosses, stars, or circles). Although each card can be sorted by color, form, or number, at any given point in the test only one dimension is correct, and the sorting rule must be inferred from oral feedback ('Correct' or 'Incorrect') given after each sort. The rule changes without warning after 10 consecutive correct sorts, and the test continues until each sorting rule is used twice, for a total of six rules or 'categories,' or until the test-taker has used all 64 cards.

The modified version consisted of the standard deck of cards plus two cardboard arrows labeled 'YES' and 'NO.' The examiner placed the appropriate arrow above the most recent sort at the same time oral feedback was given. The arrow remained in place until the next card was sorted, at which point the examiner removed the arrow and positioned the appropriate arrow above the newly sorted card. A sentence was added to the original instructions explaining the use of the arrows (i.e., 'If you are right, I will place the Yes arrow above the card; if you are wrong, I will place the No arrow above the card.').

2.2.2. Delayed matching to sample (DMTS) task

The DMTS task was administered to a subset of matched participants from the schizophrenia and control groups ($N = 16$ in each group). It was presented on an IBM-clone computer using Micro Experimental Laboratory software (MEL; Schneider, 1988). On each trial, participants had to learn a set of three colors, selected from a set of five (green, dark blue, light blue, red, and magenta). Memory was tested by means of a forced-choice recognition memory test, in which one of the initially presented target stimuli was presented again along with two foils. Thus, all five possible stimuli appeared on each trial, three as the target stimuli and the other two as foils on the memory test. Participants completed two blocks of 15 trials in a 0-delay condition and two blocks with a 6-s distraction-filled delay between study and test. Three additional practice trials were given before each block. The second block in each condition was included in order to establish the stability of working memory function and to increase the reliability of the results.

Before administering the first block of DMTS trials, a pretest was given to determine the display time needed to reach an accuracy rate of approximately 80% in the 0-delay condition. The pretest consisted of two to six blocks of 10 trials each. Based on pilot testing, a duration of 2000 ms was used as the starting point for participants with schizophrenia and a duration of 600 ms for control participants. Presentation times were altered after each block depending on the participant's performance. Possible presentation times were selected from a pre-established set of study times, ranging from 67 to 3600 ms. At the end of the pretest, a study time was selected for use on the critical trials. This time represented the shortest study time at which the participant achieved 80% accuracy or better, and can be interpreted as a measure of the speed of encoding into WM (see Hartman et al., in press, for a detailed discussion of the DMTS task).

2.2.3. Cognistat (Northern California Neurobehavioral Group, 1995)

The Cognistat is a brief neuropsychological screening measure that identifies moderate to severe neurocognitive deficits in six functional domains: orientation, attention, language, visuospatial construction, auditory memory, calculations, and reasoning.

2.2.4. Peabody Picture Vocabulary Test-R-Form M (PPVT-R; Dunn and Dunn, 1981)

The PPVT-R is a vocabulary test that uses a forced-choice format. For each item, the test-taker must select from four pictures the one that is associated with a word spoken by the examiner. Individuals can make verbal or non-verbal responses; no feedback is given. The test is terminated after six of eight consecutive items are missed.

2.3. Procedure

All interviewing and testing were conducted individually. After giving informed consent, each participant in the schizophrenia group was administered the screening and diagnostic instruments, each control participant provided background information and completed the psychiatric screening. Neuropsychological testing began with the Cognistat and the administration of one condition of the WCST. These were followed by the PPVT-R and the second WCST condition. The order of the two WCST conditions (standard and modified) was counterbalanced across participants. (Because inclusion in the study depended on matches between schizophrenia and control participants, the final sample had unequal numbers of participants with each order of administration. For each of the four possible orders, there were from 10 to 18 participants.) For participants from the DMTS study, the pretest and first set of 0- and 6-s delay DMTS trials were administered before the Cognistat; the second set of trials was administered before the PPVT-R. Time to complete testing was approximately 2–3 h, depending on participant efficiency and the need for breaks.

2.4. Scoring of the WCST

In addition to using standard scoring procedures (Heaton et al., 1993), we developed a new scoring system for evaluating the role of WM in WCST performance. The new system started with the assumption that WM demands vary as a function of two factors. The first is the amount of processing needed to select a rule, with more processing required after an error when one must inhibit the incorrect rule, then access and evaluate alternative possibilities in WM. Thus, each error that occurred after an incorrect sort was classified as having a high ‘processing load.’ Errors that occurred after correct sorts were classified as having a low ‘processing load.’

The second factor determining WM demands is the amount of stored information needed to determine how to sort a given card. We called this factor ‘memory load.’ Each error was classified as occurring under low or high memory load conditions, depending on whether the immediately preceding sort contained sufficient information to select the correct rule. Consider, for instance, errors that followed correct sorts. If an error occurred on trial n, and trial $n-1$ consisted of a correct sort that matched the key card on only one dimension (e.g., color), the memory load for trial n was considered low because one could determine the correct sorting principle simply by remembering trial $n-1$. If, however, trial $n-1$ had been a correct sort that matched on two dimensions, the error on trial n would have occurred under high memory load conditions, because information from sorts prior to trial $n-1$ would have been needed to decide which dimension was correct. Memory load following incorrect sorts similarly varied as a function of the type of sort. If an incorrect sort on trial $n-1$ matched on one dimension, memory load on trial n was considered high because memory for other previous sorts was necessary to determine the appropriate dimension. In contrast, if the incorrect sort on trial $n-1$ matched the key card on two dimensions, there is only one possibility for sorting on trial n and memory load for trial n was considered low. Overall then, memory load was high when information from multiple prior sorts was needed in order to choose the correct rule, and low when memory for trial $n-1$ was sufficient.

In order to implement this scoring system, each error was classified according to both processing and memory load, yielding four types of errors. Several types of errors that provided no information about WM were excluded, however. These included: (a) unique sorts and errors that immediately followed these sorts, because it was not possible to determine how information from the previous sorts was being used; and (b) errors on the first trial and on the sort after each category switch, when the participant did not have sufficient information to determine the correct sorting category.

Error scores also underwent several adjustments. The primary concern was that variability in the number of opportunities to make the four types of errors would bias the analyses. This bias would be expected because participants might differ in the number of sorts that matched on just one dimension and because individuals who did more poorly overall would make more errors and thus have an increased number of opportunities to make errors following errors. To control for this potential bias, each error score was divided by the number of opportunities to produce that type of error and then multiplied by 100. These calculations resulted in error percentage scores.

A second adjustment was made in order to compensate for differences among cards in the probability of making an error by chance. For example, cards that can be sorted on two dimensions can be placed under only two of the key cards, and therefore have a 50% probability of producing an incorrect sort. In contrast, cards that can be sorted on only one dimension at a time can be placed under any of three key cards, and random performance will yield errors two thirds of the time. (The only exceptions are the four cards in each deck that are identical to the key cards; for these the probability of error is zero.) In order to compensate for differences among cards, each error percentage score was weighted by the probability of making an error by chance alone. For cards that could only be sorted on one dimension, the score was divided by 0.667; otherwise, the score was divided by 0.50. Thus, the final adjusted error scores represent weighted percentage scores, and can be interpreted as the frequency with which each type of error was made.

3. Results

Non-directional hypotheses were tested, and the level of significance was set at 0.05 for all analyses except in the case of multiple comparisons, where the Rom modification of the Bonferroni procedure was used to determine the appropriate *p*-value (Olejnik et al., 1997).

During recruitment, participants in the two groups were matched on age, years of education, and gender. Successful matching was corroborated by the absence of statistical differences between groups in age or years of education ($p > 0.05$). Additional preliminary analyses showed no significant relationship between length of illness and performance on the WCST in the schizophrenia group. In addition, an ANOVA in which the schizophrenia group was subdivided into three subgroups (disorganized, paranoid, and undifferentiated) showed no effect of type of schizophrenia on WCST performance.

3.1. Overall performance and the pattern of perseverative and non-perseverative errors

Analyses using the standard scoring system were limited to those scores most important for testing the study's hypotheses. These included the number of categories completed, a measure of overall performance, plus two types of errors—perseverative and non-perseverative (see Table 1). Because unique errors were rare and with one exception not significantly different from zero for any group of participants in any condition, no formal analyses were conducted with these scores.

The first analysis examined WCST category scores in a three-way ANOVA with group and order of administration (standard first vs. modified first) as between-subjects variables and test version (standard vs. modified) as a within-subjects variable. Results showed a main effect of group, $F(1,51) = 15.71$, $p = 0.0002$, with worse performance for the schizophrenia group. (Note that one participant with schizophrenia did not complete the second administration, resulting in a sample size of 55.) No effects involving test version or order of administration approached significance. Perseverative and non-perseverative errors were examined by means of a four-way ANOVA, with group and order of administration as between-

Table 1
WCST scores for the control and schizophrenia groups

	Standard WCST		Modified WCST	
	Control M (SD)	Schizophrenia M (SD)	Control M (SD)	Schizophrenia M (SD)
Standard 1ST				
Categories	4.3 (0.9)	2.2 (1.8)	4.3 (0.8)	2.9 (2.1)
Errors				
Perseverative	6.6 (1.7)	13.7 (9.7)	3.9 (1.2)	11.2 (7.9)
Non-perseverative	5.5 (2.6)	10.7 (6.3)	3.8 (2.1)	8.2 (4.8)
Modified 1ST				
Categories	3.8 (1.6)	2.3 (1.9)	3.8 (1.2)	2.4 (1.6)
Errors				
Perseverative	6.4 (4.0)	11.4 (8.4)	7.3 (4.7)	15.3 (11.1)
Non-perseverative	6.1 (5.7)	10.6 (7.6)	6.3 (3.6)	8.9 (5.7)

subjects variables, and test version and type of error as within-subjects variables. Results revealed significant effects of group, $F(1,51)=17.88$, $p<0.0001$, and of error type, $F(1,51)=4.76$, $p=0.03$. Individuals with schizophrenia made more errors, and most errors were perseverative. There was no interaction between group and error type, indicating equivalent increases in both types of errors in schizophrenia. There was a significant interaction between order and test version, however, $F(1,51)=7.39$, $p<0.009$. A follow-up ANOVA for the individuals who received the modified WCST second showed a significant effect of test version, with fewer errors in the modified condition, $F(1,19)=8.18$, $p=0.01$. In contrast, for individuals who received the modified condition first, there was no difference in the number of errors in the two versions of the test ($p>0.20$), although there was a nearly significant interaction between error type and test version ($p=0.06$). Separate analysis of perseverative and non-perseverative errors for these participants showed that the second, standard condition resulted in a significant reduction in perseverative errors, $F(1,32)=6.22$, $p=0.02$, but not non-perseverative errors. Therefore, taking the test twice consistently led to a reduction in perseverative errors. In addition to this general practice effect, the availability of cues in the modified condition led to fewer of both types of errors if it was given second.

3.2. The role of working memory

Preliminary analyses examined the patterns of Pearson-product correlations among adjusted error scores and between adjusted error scores and scores based on the standard scoring system (see Table 2). Correlations among the adjusted error scores were all statistically significant and moderate in size, with the exception of the correlation between low-memory/low-processing load and low-memory/high-processing load errors, which only showed a trend towards significance (p's$=0.09$). The median correlation equaled 0.41. After correcting for multiple correlations, all remained significant except the correlation between low-memory/low-processing load and high-memory/high processing load errors on the modified WCST. Correlations between adjusted error scores and the more global scores (i.e., categories, perseverative, and non-perseverative errors) were all significant and somewhat larger, with the median absolute size of these correlations equal to 0.69. All remained significant after correcting for multiple correlations, with the exception of the correlation between non-

Table 2
Pearson product moment correlations among adjusted error scores and between the adjusted error scores and scores based on the standard scoring system

	Low ML		High ML		Categories	Perseverative errors	Non-perseverative errors
	Low PL	High PL	Low PL	High PL			
Standard WCST							
Low ML							
Low PL	–	0.23	0.57	0.43	– 0.65	0.50	0.49
High PL		–	0.47	0.46	– 0.47	0.40	0.54
High ML							
Low PL			–	0.71	– 0.92	0.82	0.69
High PL				–	– 0.74	0.71	0.70
Modified WCST							
Low ML							
Low PL	–	0.24	0.40	0.35	– 0.63	0.30	0.53
High PL		–	0.42	0.40	– 0.40	0.52	0.28
High ML							
Low PL			–	0.71	– 0.87	0.90	0.40
High PL				–	– 0.71	0.68	0.50

ML = memory load; PL = processing load.

perseverative errors and low-memory/high processing load errors on the modified WCST. Thus, the adjusted error scores appear to reflect unique properties of performance, while still showing significant relationships with the original scoring system.

A five-way ANOVA was conducted on the adjusted error scores (see Table 3), with group and order of administration as between-subjects variables, and test version, processing load, and memory load as within-subjects variables. Results showed a main effect of group, $F(1,51) = 15.19$, $p = 0.0003$, with more frequent errors for individuals with schizophrenia. There were also effects of processing load, $F(1,51) = 98.21$, $p < 0.0001$; memory load, $F(1,51) = 5.91$, $p = 0.02$; and an interaction between them, $F(1,51) = 9.41$, $p = 0.004$. Errors were more frequent when WM demands were higher, and fewest errors were made when both memory and processing load were low. There were also a number of three-way interactions involving test version and order of administration: between test version, order, and memory load, $F(1,51) = 8.40$, $p = 0.006$; between test version, order, and processing load, $F(1,51) = 6.10$, $p = 0.02$; as well as a trend for a three-way interaction between order, test version, and group ($p = 0.07$). In order to interpret these interactions, follow-up tests were conducted separately for each version of the test.

For the standard WCST, there were main effects of processing load, $F(1,52) = 68.14$, $p < 0.0001$, and memory load, $F(1,52) = 4.30$, $p = 0.04$, as well as an interaction between them, $F(1, 52) = 12.59$, $p = 0.0008$. There was a near significant three-way interaction between processing load, memory load, and order of administration, $F(1,52) = 4.02$, $p = 0.0501$. Together these indicate that higher processing and memory load increased the frequency of errors, and that the effects of processing load were more marked for the first administration. Thus, with practice, WM demands had a reduced effect on the standard WCST. There was also a main effect of group, $F(1,52) = 11.63$, $p = 0.001$, and a three-way interaction between processing load, memory load, and group, $F(1,52) = 6.59$, $p = 0.01$. Individuals with schizophrenia made more frequent errors, and higher WM demands led to a greater increase in errors for them than for control participants.

For the modified WCST, there were fewer effects involving WM demand. There was a main effect of processing load, $F(1,51) = 54.49$, $p < 0.0001$, with more frequent errors when the load was higher. Memory load interacted with the order of administration, $F(1, 51) = 6.16$, $p = 0.02$, and there was a trend towards an interaction between order and processing load ($p = 0.09$). These reflected a diminished effect of WM demand, especially memory load, when the

Table 3
Adjusted error scores, classified according to processing and memory load

	Standard WCST		Modified WCST	
	Control M (SD)	Schizophrenia M (SD)	Control M (SD)	Schizophrenia M (SD)
Standard 1^{ST}				
Low memory load				
Low processing load	1.6 (3.2)	17.8 (21.7)	3.2 (4.2)	25.8 (36.5)
High processing load	29.2 (35.7)	61.7 (39.9)	20.1 (32.5)	50.9 (30.1)
High memory load				
Low processing load	9.0 (10.4)	39.6 (29.2)	2.5 (4.4)	27.6 (25.4)
High processing load	48.0 (25.1)	55.3 (33.0)	11.2 (15.8)	47.1 (37.3)
Modified 1^{ST}				
Low memory load				
Low processing load	4.8 (9.1)	15.1 (21.9)	2.5 (5.0)	14.3 (17.1)
High processing load	33.1 (37.2)	59.1 (39.1)	36.1 (38.3)	45.9 (44.0)
High memory load				
Low processing load	15.9 (23.7)	37.9 (29.4)	14.5 (17.3)	35.7 (27.6)
High processing load	22.0 (27.2)	43.7 (37.1)	41.2 (28.9)	57.3 (32.3)

These adjusted error scores represent the number of errors, divided by the number of opportunities and the guessing rate, and may be thought of as weighted percentages.

modified WCST was given second. The only effect involving group was a main effect, $F(1, 51) = 14.63$, $p = 0.0004$, signifying an overall higher error rate.

3.3. Relationship of WCST to DMTS performance

For participants who also completed the DMTS task, the relationship between this WM task and the standard WCST was examined. These analyses focused in particular on the presentation times required to perform to a criterion of 80% accuracy under 0-delay conditions of the DMTS task. This measure of the speed of WM encoding was significantly correlated with the category score ($r = -0.54$, $p = 0.001$) and the total number of errors on the WCST ($r = 0.58$, $p = 0.0006$). Thus, there was a strong relationship between WCST impairment and the efficiency of encoding into WM. A further analysis tested whether controlling for WM encoding would reduce group differences on the standard WCST. To test this, two ANCOVAs were carried out, one with category scores and one with error scores, using WM encoding speed as the covariate. For category scores, the effect of the covariate was significant, $F(1,29) = 4.45$, $p = 0.04$, and the difference between control and schizophrenia groups was eliminated ($F < 1$). For perseverative and non-perseverative errors, the ANCOVA again revealed a significant effect of the covariate, $F(1,29) = 9.75$, $p = 0.004$, and no effect of group ($p > 0.10$). There was a trend towards more perseverative than non-perseverative errors ($p = 0.09$). The interactions between error type and group and between error type and WM encoding speed were both significant, however [$F(1,29) = 4.31$, $p = 0.047$; $F(1,29) = 4.74$, $p = 0.04$]. Follow-up tests showed that controlling for speed of encoding eliminated the group differences for non-perseverative errors ($F < 1$), but not perseverative errors, $F(1,29) = 6.59$, $p = 0.02$. Thus, slowed encoding for individuals with schizophrenia was related to lower category scores and higher error rates, and particularly affected the number of non-perseverative errors.

3.4. Neuropsychological test performance and its relationship to the WCST

Table 4 shows mean scores for each neuropsychological test other than the WCST. On the Cognistat, 21 of the 28 individuals with schizophrenia were impaired on at least one subtest, with 12 of these scoring in the impaired range on more than one subtest. In contrast, there were only seven control participants with scores in the impaired range; in each case, only one subtest was involved. Twelve individuals with schizophrenia had at least one subtest score that was moderately to severely impaired, whereas for the control group all of the scores in the impaired range were in the mild range, with the exception of one, which was in the moderately impaired range. An overall MANOVA was then conducted with all subtests of the Cognistat except for the Comprehension subtest, on which all participants received perfect scores. Results indicated a main effect of group, $F(6,44) = 2.79$, $p < 0.01$. Follow-up t-tests showed significant impairments in the schizophrenia group on four of the subtests: Orientation, $t(53) = 2.64$, $p = 0.01$, Memory, $t(53) = 2.76$, $p = 0.008$, Similarities, $t(53) = 2.58$, $p = 0.01$, and Judgment, $t(53) = 2.83$, $p = 0.007$, with a trend towards reduced performance on the Repetition and Constructional Ability subtests (p's < 0.10). With p-value cutoffs corrected for multiple comparisons, the t-tests for Orientation, Memory, and Judgment remained significant; the t-test for Similarities just missed significance. On the PPVT-R, individuals with schizophrenia had reduced vocabulary scores, $t(53) = 3.49$, $p = 0.001$. The overall pattern of neuropsychological test results indicates multiple cognitive impairments in this sample of individuals with schizophrenia, with particular deficits

Table 4
Neuropsychological test performance

	Control M (SD)	Schizophrenia M (SD)
Cognistat		
Orientation[a]	11.9 (0.3)	11.1 (1.5)
Memory[a]	11.5 (1.0)	10.1 (2.4)
Attention	7.9 (0.3)	7.7 (0.9)
Comprehension	6.0 (0)	6.0 (0)
Repetition[b]	12.0 (0)	11.9 (0.5)
Naming	7.8 (0.4)	7.6 (0.6)
Constructions[b]	5.4 (0.8)	4.9 (1.2)
Calculations	3.8 (0.5)	3.7 (0.7)
Similarities[a]	7.1 (1.1)	5.99 (2.1)
Judgment[a]	4.9 (1.2)	3.9 (1.5)
Peabody Picture Vocabulary Test[a]	104.6 (22.1)	86.2 (16.5)

[a] $p < 0.05$.
[b] $p < 0.10$.

in memory and conceptual abilities, as well as in vocabulary. Basic attention and language skills were unimpaired.

The relationship between performance on the WCST and these neuropsychological tests was also examined. Correlations showed that two subtests of the Cognistat were significantly correlated with the total number of errors on the standard WCST: Repetition ($r = -0.32$, $p = 0.02$) and Memory ($r = -0.28$, $p = 0.04$). When p-value cutoffs were corrected for multiple comparisons, both remained significant. Given the absence of deficits in Comprehension and Naming, the correlation involving Repetition may reflect attentional rather than language deficits. The correlation between WCST errors and PPVT-R vocabulary was also significant ($r = -0.47$, $p = 0.0003$).

4. Discussion

As expected, individuals with schizophrenia demonstrated significant impairments on the WCST. They completed fewer categories and made more errors than the control group. The focus of the current study was to evaluate the extent to which these impairments reflected deficits in WM. Before discussing the findings regarding schizophrenia, however, we first review the evidence that WM makes an important contribution to performance on the WCST; it appears that the test taxes WM capacity even in healthy individuals.

The first piece of support for the role of WM on the WCST is the presence of both perseverative and non-perseverative errors in all individuals, with a greater number of the former. This pattern is predicted by theoretical conceptualizations of WM and is consistent with the results of computer simulations of the WCST (Dehaene and Changeux, 1991; Kimberg and Farah, 1993). When test-takers are unable to properly update WM and integrate all the relevant information, they make errors and tend to make decisions based on prior knowledge that is most salient, namely the category rule that was most recently reinforced.

More direct evidence of the contribution of WM to WCST performance came from our analysis of WM demands. All participants made more errors when memory load was high, i.e., when information from more than the most recent sort was needed in order to establish the current sorting rule. Errors were also more frequent after an incorrect than a correct sort, showing an effect of processing load. After an incorrect sort, the test-taker must engage in additional controlled processing in WM to select an appropriate rule for the subsequent sort. These two types of WM demand also interacted, such that error rates were highest when both memory load and processing load were high. Interestingly, the effects of WM demand were reduced when the WCST was administered a second time. Apparently practice with the materials and types of processing required by the test diminished the impact of memory and processing load on performance. Furthermore, on the modified WCST, these practice effects were stronger for memory load than processing load. This finding is understandable, given that the cues should primarily decrease storage demands, by reducing the amount of information to be stored and providing more time for encoding.

An additional way of assessing the effects of WM on performance involved a comparison of performance on the standard and modified versions of the WCST. For all participants, the cues in the modified version of the test reduced the number of errors, although only when the modified version of the test was administered second. The benefit of cues did not appear the effect of practice alone, however, since taking the standard WCST second did not show a corresponding decrease in the number of errors. It is noteworthy that the benefits of cues did not extend to the number of categories completed. This suggests that the cues reduced the difficulty of encoding new information into WM, but did not help with other aspects of WM processing such as integrating information across sorts and evaluating possible sorting rules. Alternatively, the category scores are less sensitive to change in performance.

To summarize findings related to the role of WM on the WCST, we demonstrated converging evidence that WM is important to good performance. The pattern of errors was consistent with theories of WM, and error rates were closely tied to the changing demands for storing and processing information throughout the test. Cues produced a significant benefit, reducing errors and the impact of WM demand, although this effect occurred only after participants had experience with the standard version of the test.

With regard to impairments among individuals with schizophrenia, the results clearly indicated that deficits in WM contribute to their poor performance. On the standard WCST, WM demands had a greater negative impact on the schizophrenia group than the control group: when WM demands were high, individuals with schizophrenia were relatively more likely to make errors. In addition, visual cues reduced the differential impact of WM demand and partially helped the schizophrenia group compensate for their WM deficits. Although they still performed more poorly than the control group on the modified WCST, the two groups showed the same pattern of errors in relation to WM demand. Thus, individuals with schizophrenia demonstrated an increased sensitivity to the WM demands of the test that disappeared when external memory cues were provided.

Despite the evidence for WM impairments in the schizophrenia group, the increases in perseverative and non-perseverative errors were of similar magnitude. This pattern suggests that WM dysfunction, although present, was not severe, since disproportionate increases in perseverative errors tend to occur only when WM is extremely impaired. Similarly, there was no evidence for reduced cognitive flexibility. Although inflexibility is often used to describe the poor performance of individuals with schizophrenia on the WCST, the current findings provide little support for this hypothesis. Indeed, factor analytic studies of the WCST that are cited as evidence of inflexibility may have been over-interpreted (Koren et al., 1998; Sullivan et al., 1993). These studies show that the factor most consistently associated with large differences between schizophrenia and control groups has a high loading of perseverative errors; however, it also includes other scores, such as the number of categories, the total number of errors, the number of trials to first category, and the total number of correct sorts. Thus, perseverative errors are correlated with other indices of performance and may represent a non-specific marker of impairment in schizophrenia. In addition, as we have previously noted, perseverative errors do not necessarily reflect inflexibility but may also occur as a result of WM failure.

Another finding of this study is that the availability of memory cues did not fully remediate poor WCST performance in schizophrenia. There were group differences even on the modified WCST, and the cues did not reduce the amount of impairment as measured by either category scores or perseverative and non-perseverative error scores. In addition, the schizophrenia group made more errors than the control group on the modified WCST even when WM demands were minimal, i.e., when a cue was present and the previous sort was correct and provided full information about which sorting rule to use next. For healthy older adults, who also have documented declines in WM, visual cues are sufficient to completely eliminate age differences, and their performance on this modified version of the WCST is equivalent to that of healthy, younger adults given the standard WCST (Hartman et al., 2001). In contrast, the current findings suggest that memory cues did not fully address the impairment in schizophrenia. Although it is possible that cues provided limited benefit to individuals with schizophrenia because they simply did not use them, this explanation seems unlikely, however, because in some respects the cues helped those with schizophrenia more than control participants. In no analysis did the control group show a greater benefit from the cues. It is more likely that other aspects of WM or other cognitive deficits not ameliorated by the cues remain an additional source of impairment on the WCST.

Although external cues did not fully remove group differences on the WCST, for the most part controlling for speed of encoding into WM did. Our prior study of performance on the DMTS indicated that individuals with schizophrenia require substantially more time to encode information into WM, and that slowing completely accounted for their inability to maintain information in WM across a distraction-filled delay (Hartman et al., in press). In the current study, there was a strong relationship between slowed encoding into WM and WCST errors. Furthermore, statistically controlling for DMTS encoding speed mostly eliminated group differences on the WCST. Thus, our findings indicate that inefficient activation of information in WM may be the core deficit underlying poor performance on the WCST in schizophrenia.

Reduced speed of encoding into WM may also reflect a generalized slowing of information processing. Such an interpretation is consistent with other evidence of slowing in schizophrenia (Brebion et al., 1998, 2000), and with findings of significant correlations between other tests of WM and performance on speeded tests of attention (e.g., Digit Symbol Substitution Test, Stroop Test, cancellation tests) (Brebion et al., 1998, 2000; Gold et al., 1997; Salamé et al., 1998; Stratta et al., 1997). As suggested by Salthouse (1996) in the context of research on cognitive aging, cognitive slowing may have multiple effects on the ability to process information. One such effect, of course, is that an individual may be unable to complete a task in the available time. A less obvious consequence of slowing, however, occurs when a task involves multiple steps carried out in succession. In this situation, slowing of each step may result in the loss of the products of preceding steps before they can be used. The latter could explain the current findings. If individuals with schizophrenia are slow to execute each step in the processing of the WCST cards, they may lose track of necessary information before they have the opportunity to apply it. This could occur even at points in the test where WM demands are at their lowest.

A generalized slowing of information processing may also explain the findings from previous remediation studies with the WCST. Overall, this literature has found that explaining the rules of the test prior to the beginning of testing provides little benefit to individuals with schizophrenia (Goldberg et al., 1987; Stuss et al., 1983), but that repeated instructions, trial-by-trial instructions, or extensive training in the cognitive components of the WCST do lead to significant improvement (Bellack et al., 1990; Goldberg et al., 1987; Goldman et al., 1992; Green et al., 1992; Kern et al., 1996; Metz et al., 1994; Stratta et al., 1994). Having the schizophrenia group verbalize their strategy after each sort also leads to better performance (Perry et al., 2001). In some cases, the improvements reduce or eliminate impairments (Delahunty et al., 1993) and are at least partially maintained over time (Bellack et al., 1990; Delahunty et al., 1993; Green et al., 1992; Kern et al., 1996; Metz et al., 1994). These findings indicate that remediation of various aspects of the test is useful, but only if information is presented repeatedly in the course of training or prompted continuously during the test. It is possible that slowed processing may underlie all of these findings, in that it causes individuals with schizophrenia to lose information before being able to use it and therefore reduces their ability to learn skills that might improve their performance.

Generalized inefficiency of information processing may also explain the relationship of performance on the WCST to a range of other measures of cognitive function. In the current study, deficits were noted in multiple domains, including attention, memory, conceptual ability, and vocabulary. WCST errors were related to some but not all of these measures. Additional relationships have been observed in previous studies, and the lack of more extensive correlations in the current study is probably due to the limited scope of our neuropsychological battery. For instance, relationships between WCST performance and abstract thinking, concept attainment, set-shifting, and verbal fluency, episodic memory have been documented in other studies (Glahn et al., 1999; Gold et al., 1997; Sullivan et al., 1993). If information processing speed was impaired, one would expect correlations among many areas of cognitive functions, with strongest relationships for tasks having prominent speed and attention components.

As a final point, it should be noted that reduced speed of processing can be differentiated from generalized cognitive decline. For instance, in the current study individuals with schizophrenia exhibited a lower level of overall intellectual functioning, as reflected in reduced vocabulary scores, and vocabulary ability was significantly correlated with WCST errors. In order to test whether reduced intellectual functioning could account for their impairments on the WCST, we conducted a set of statistical analyses of the WCST using analysis of covariance procedures, with vocabulary scores as the covariate. The results showed significant effects of the covariate but otherwise the identical pattern of group effects as the original analyses. Thus, general intellectual level could not explain the impairments of the schizophrenia group on the WCST. This in turn suggests that performance deficits on the WCST result from a specific information processing deficit in schizophrenia rather than by generalized cognitive dysfunction.

5. Conclusions

The results of the current study converge on the conclusion that poor performance among individuals with schizophrenia on the WCST is related to deficits in WM function. These deficits in turn appear to involve a generalized inefficiency of information processing in WM that prevents individuals with schizophrenia from using available information in the service of a goal. The deficits are exacerbated when WM demands are high, and are partially alleviated when visual cues serve as external memory for the immediately preceding sort. These deficits are also captured by measures of slowing in WM, as observed on the DMTS task. The observed deficits in WM are likely to represent a widespread impairment in information processing speed and may underlie a range of deficits on both lower level tasks such as speed of processing (Brebion et al., 1998, 2000), orienting (Öhman et al., 1986), and selective attention (Brebion et al., 2000), and on tests of higher level abilities, such as executive function, memory and conceptualization.

Acknowledgements

This research was supported in part by a grant from the University of North Carolina Research Council to the first author. Portions of these data were presented at the Meeting of the International Neuropsychological Society (Denver, CO, February 2000). The authors gratefully the assistance of Rayne Lane and Heather McCann in data collection.

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