Journal of Abnormal Psychology
1997, Vol. 106, No. 2, 315–324

0021-843X/97/$3.00

Impaired Precision, but Normal Retention, of Auditory Sensory ("Echoic") Memory Information in Schizophrenia

Daniel C. Javitt, Rael D. Strous,
Sandra Grochowski, and Walter Ritter
Albert Einstein College of Medicine/Bronx Psychiatric Center

Nelson Cowan
University of Missouri—Columbia

Working memory is the type of memory that allows one to hold information in mind while working on a task or problem. The present study investigated attention-independent auditory sensory ("echoic") memory in 18 schizophrenic participants and 17 controls. Schizophrenic participants showed impaired delayed tone matching performance in comparison with controls. However, when groups were matched for performance at 1 s by varying the difficulty of the task across groups, schizophrenic participants showed normal retention of information as reflected in normal tone matching performance. These findings demonstrate that schizophrenic participants show working memory deficits even in extremely simple tasks and that the critical deficit in schizophrenia may be in the sensitivity of the system rather than the duration for which memory traces are retained.

Schizophrenia is a complex neuropsychiatric disorder associated with disturbances in perception, behavior, and cognition. A significant goal of recent research in schizophrenia has been the development of unifying themes that could account for the complex constellation of signs and symptoms observed in schizophrenia. One particularly fruitful area of recent research has been a focus on working memory dysfunction as a potential basic mechanism underlying cognitive dysfunction in schizophrenia (reviewed in Goldman-Rakic, 1994). Working memory, broadly defined, is the type of memory that allows one to hold information in mind while working on a task or problem (Baddeley, 1986). Although early theories of working memory (e.g., Broadbent, 1958) postulated the existence of a single system underlying all aspects of such memory, more recent findings (Baddeley, 1986; Cowan, 1988) require the presence of at least two distinct types of information-processing mechanisms: (a) attention-dependent storage mechanisms, which are regulated by executive control systems and require effort on the part of the participants and (b) attention-independent storage mechanisms, which hold information automatically in a vivid and accessible form for a short time.

Studies of working memory in schizophrenia have focused primarily on attention-dependent processing, using tests such as the spatial-delayed response task (Park & Holzman, 1992), the visual "AX"-type continuous performance task (AX-CPT; Cohen & Servan-Schreiber, 1993), and the Wisconsin Card Sorting Test (Kolb & Whishaw, 1983). Such tests are all heavily dependent on processing within prefrontal association brain regions (Goldman-Rakic, 1994). Disturbances in Wisconsin Card Sorting Test performance, moreover, have been correlated with decreased prefrontal "activation" as reflected in regional cerebral blood flow (Weinberger, Berman, & Zec, 1986). By contrast, relatively few studies have assessed attention-independent components of working memory, leaving unresolved the degree to which working memory dysfunction in schizophrenia is restricted to tasks that depend primarily on prefrontal processing.

The present study investigated a working memory component termed auditory sensory or "echoic" memory, which consists of a vivid recollection of the acoustic qualities of a sound. Such recollections typically persist for up to approximately 30 s after presentation of auditory stimuli (for reviews, see Cowan, 1984, 1988), whether or not such stimuli are attended at the time of presentation. Thus, as opposed to working memory components that localize primarily to prefrontal cortex, auditory sensory memory appears to function largely in an attention-independent fashion.

Performance of the auditory memory system can be examined most simply in tasks in which two presented sounds are separated by a variable interstimulus interval (ISI) and the participant is required to compare them to make a subtle acoustic judgment (e.g., to decide whether the sounds are the same or different). When the ISI is silent, tasks of this nature result in a performance level that is high at short ISIs and declines exponentially toward an asymptotically low level as the ISI increases beyond about 10 s (e.g., Berliner & Durlach, 1973; Crowder, 1982; J. D. Harris, 1952; Massaro, 1970b; Moss, Myers, & Filmore, 1970; Pisoni, 1973). The decline of auditory sensory memory with poststimulus time correlates closely with

Daniel C. Javitt, Rael D. Strous, Sandra Grochowski, and Walter Ritter, Departments of Psychiatry and Neuroscience, Albert Einstein College of Medicine/Bronx Psychiatric Center; Nelson Cowan, Department of Psychology, University of Missouri—Columbia.

This research was supported by U.S. Public Health Service Grants R29 MH49334, R01 HD21338, and R01 N530029; a grant from the National Alliance for Research on Schizophrenia and Affective Disorders; and by the Zara and Bernad Jakubovitz Fund for Brain Research. We thank Anne-Marie Shelley for her assistance in paradigm implementation.

Correspondence concerning this article should be addressed to Daniel C. Javitt, who is now at the Division of Cognitive Neuroscience and Schizophrenia, The Nathan Kline Institute for Psychiatric Research, 140 Old Orangeburg Road, Orangeburg, New York 10962. Electronic mail may be sent via Internet to javitt@iris.rfmh.org.

changes in the electrophysiological state of primary and association areas of the auditory temporal cortex (Lu, Williamson, & Kaufman, 1992; Sams, Hari, Rif, & Knuutila, 1993). In two-stimulus comparison tasks using tonal stimuli, the primarily automatic nature of memory retention is revealed in that the nature of the participant's silent mental activity during the ISI matters little, but the effects of an intervening sound during the ISI are large (Deutsch, 1970; Keller, Cowan, & Saults, 1995; Massaro, 1970b; Pechmann & Mohr, 1992). Furthermore, memory is very good immediately after the acoustic stimulus, even for sounds that are unattended at the time of their presentation, and is lost steadily and dramatically as the testing delay increases to about 10–20 s (Cowan, Lichty & Grove, 1990; Eriksen & Johnson, 1964; Glucksberg & Cowen, 1970; Norman, 1969).

Performance in a two-stimulus task with a variable ISI depends not only on the duration of auditory sensory memory but also on the difficulty of the discrimination in relation to the precision of the memory representation (Berliner & Durlach, 1973; Massaro, 1970a). It is likely that an acoustic stimulus such as a tone leaves a record in long-term memory, although that record is relatively imprecise (Cowan, 1984; Cowan, Winkler, Teder, & Naatanen, 1993). If the two-tone discrimination is easy enough, the long-term record of the first tone may suffice for the task, resulting in good performance even at relatively long intervals, and auditory sensory memory is not required for performance of the task. Conversely, if the discrimination is difficult enough, even the more detailed auditory sensory memory trace will not suffice for the discrimination. The finding of ISI-dependent memory thus is obtained only when two conditions are satisfied: The precision of the temporary sensory memory representation of the first tone in a pair initially must be sufficient for the participant to carry out the discrimination well, and the long-term memory record alone must be insufficient for the participant to do so.

We have previously reported that schizophrenic participants show significant deficits in auditory sensory memory performance (Strous, Cowan, Ritter, & Javitt, 1995). The present study addressed the degree to which the deficit in tone matching performance in schizophrenia reflects impairments in the precision with which the auditory sensory memory functions, as compared with the rate at which auditory sensory information decays. To distinguish between these two possibilities, we examined sensory memory in a two-tone discrimination task that we conducted at varying levels of task difficulty and ISI. Tones within each pair in the two-tone task either could be identical or could differ in pitch by a fixed percentage of base frequency. In some trial blocks, however, the frequency differences (Δf) amounted to 20% of the first tone's pitch, corresponding to an easy discrimination, whereas, in other blocks, the differences were only 5%, corresponding to a more difficult discrimination. In our pilot study, which used a 300-ms delay, schizophrenic participants performed similarly in a 20% Δf discrimination condition as did controls in a 5% Δf condition (Strous et al., 1995). A second experiment (Experiment 2) was conducted to assess no-delay tone matching for between-tones pitch differences of even less than 5%; the goal was to determine the degree to which differential task difficulty (Chapman & Chapman, 1978; Strauss, 1994) might have affected the overall pattern of results.

These experiments demonstrate that schizophrenic participants show a robust deficit in the ability to match two tones even after a brief ($\leq$1 s) delay. However, the present study also demonstrates that if the level of between-tones pitch separation is adjusted so that schizophrenic participants perform equivalently to control participants at 1-s delay—that is, if schizophrenic participants are tested at an easier level of between-tones pitch separation than controls—the subsequent performance decrement between 1 and 20 s is equivalent between groups. Thus, schizophrenic participants show impaired precision of the auditory sensory memory system at all time points but normal decay of memory strength over time.

Experiment 1: Tone Matching at Varying ISIs

To assess tone matching ability in schizophrenic patients relative to nonpsychiatric controls of similar age and IQ, we tested both groups in their abilities to detect between-tones pitch differences of either 5% or 20% at ISIs ranging from 0 to 20 s. Tests were conducted in the presence and absence of a visual distractor task in which participants read single digits from a computer screen. Also, as a comparison condition, participants were tested in forward and backward digit span. Digit span tests participants' ability to repeat series of numbers after a brief delay and relies heavily on the short-term phonological memory system (Baddeley, 1992). Phonological short-term memory depends on vocal or subvocal rehearsal of chunks of information and, thus, differs fundamentally from auditory sensory memory, which maintains representations of stimuli without rehearsal.

Method

Participants

Informed consent was obtained from 18 chronic schizophrenic participants and 17 nonpsychiatric control participants of similar age and IQ. All participants were of normal hearing by self-report. Schizophrenic participants, recruited from the schizophrenia research unit of the Bronx Psychiatric Center, had a mean ($\pm$ *SE*) current hospitalization stay of 36 $\pm$ 12 months (*Mdn* = 9.5, range = 3–171) before testing. Schizophrenic participants were diagnosed, according to the *Diagnostic and Statistical Manual of Mental Disorders* (3rd ed., rev.; *DSM-III-R;* American Psychiatric Association; 1987), by a board-certified attending research psychiatrist using semistructured clinical interviews, chart review, and discussion with family and mental health professionals familiar with the case as required. Participants with *DSM-III-R* Axis I disorders other than schizophrenia, including alcoholism or substance abuse, were excluded from the study, as were patients with clinically apparent neurological abnormalities or those with significant musical training. The mean ($\pm$ *SE*) neuroleptic dose among schizophrenics was 1,825 $\pm$ 254 chlorpromazine equivalents per day. Twelve participants were also taking anticholinergic medication. Control participants were recruited by personal contact from among the faculty, trainees, and staff of the Bronx Psychiatric Center. Schizophrenic and control participants were of similar age (39.0 $\pm$ 2.4 and 37.6 $\pm$ 2.1 years, respectively), sex (15 men and 3 women and 13 men and 4 women, respectively), and Quick Test (Ammons & Ammons, 1962) IQ (96.3 $\pm$ 2.0 and 99.6 $\pm$ 1.9, respectively). Participants were paid a small honorarium for taking part in the study.

Design

The procedure consisted of four subtests. First, participants were administered a brief screening hearing test to ensure that they could detect the presented tones. Second, participants were tested on their ability to detect tone mismatches when there was no delay between the first and second tones. No-delay tone matching was tested in both an easy discrimination condition (20% Δf between tones) and a difficult condition (5% Δf). Third, participants were tested on their ability to detect tone mismatches when the time between tones varied from 1 to 20 s. This subtest was administered twice at each of the two levels of Δf: once when participants had no other concurrent task (no-distraction condition) and once when they were required to read single digits from a computer screen (distraction condition). Fourth, participants were tested on their ability to perform a comparison task (digit span) that was similar in terms of overall duration and delay intervals to the delayed tone matching task but did not require echoic memory for its performance. Tone matching performance (percentage of correct matches) was assessed as a function of three factors: (a) time between tones, (b) pitch separation between first and second tones (discrimination difficulty), and (c) presence or absence of a visual distractor task in which participants read digits aloud from a computer screen between tones. Results were examined via analyses of variance (ANOVAs) with the between-groups variable of diagnostic group and the within-group variables of time, discrimination difficulty, and distraction.

Procedure

Screening hearing test. Participants were recruited for this study only if they were of normal hearing by self-report and ward behavior. Adequate hearing was confirmed by having participants detect tone intensities 10 dB lower than those used in the tone matching tasks (75 dB SPL). Twelve tones corresponding in pitch to those used in the delayed tone matching test were presented in pseudorandom fashion at a nominal intensity of 65 dB SPL by a NeuroScan STIM system using auditory brainstem response type (ABR-type) intraaural stimulators. The time interval between tones varied between 1 and 40 s in pseudorandom fashion. Participants were required to indicate, with their hand or verbally, exactly when they heard each sound. All participants were able to detect all 12 presented tones. No participants were excluded on the basis of hearing threshold.

No-delay tone matching. To assess pitch discrimination ability with no delay between tones (0-s interval), we constructed 200-ms tones in which the first half of the tone (100 ms) was at one of the standard frequencies and the second half was the same, higher, or lower in pitch by 5% or 20%. The composite tone was tapered with a rise–fall time of 10 ms. Participants were instructed to respond verbally as to whether the composite tone remained the same throughout or whether the end differed in pitch from the beginning. The intertrial interval was 5 s. Three different base frequencies (500, 1000, and 2000 Hz) were used to minimize the degree to which participants learned to recognize reference stimuli across trials. For easy discriminations, the second segment of each stimulus differed by 20% in pitch from the first segment. For difficult discriminations, target stimuli differed by 5%. Stimuli were presented in two blocks of 12 stimuli each, segregated according to level of difficulty. In each block, 50% of trials contained composite tones that were the same throughout, 25% of trials contained tones in which the end was higher in pitch than the beginning by the appropriate amount (5% or 20% Δf), and 25% of trials contained tones in which the end was lower in pitch than the beginning. All tones were generated with a NeuroScan STIM system presented through ABR-type intraural stimulators at a nominal intensity level of 75 dB SPL. All participants were tested first in the easy condition (20% Δf) and then in the difficult condition (5% Δf). Before formal testing, we familiarized participants with the testing apparatus and procedure by having them listen to the tones used for the easy discrimination and by providing them feedback as to whether their responses were correct or incorrect. Participants typically required exposure to 5–10 stimuli before indicating that they understood the testing procedure. Portions of the no-delay tone matching data have been reported previously (Strous et al., 1995).

Delayed tone matching. To assess delayed tone discrimination ability, we presented tone pairs in which the second, target stimulus was either identical to the preceding reference tone or differed by 5% (difficult task) or 20% (easy task) in pitch. Each tone was 100 ms in duration with a rise–fall time of 10 ms. Six ISIs were used (1, 3, 5, 10, 15, and 20 s). Participants were asked to respond verbally as to whether the second tone in each pair was the same or different in pitch from the immediately preceding stimulus. Participants were cued with a visual message ("first tone" or "second tone") immediately (500 ms) preceding the auditory stimuli. Stimuli were presented in four blocks of 72 tone pairs (12 tone pairs at each ISI), segregated according to level of difficulty and presence or absence of distraction. Blocks were presented in constant order (easy, no distraction; difficult, no distraction; easy, distraction; and difficult, distraction). At each ISI, 6 tone pairs contained tones that were identical in pitch, 3 tone pairs contained tones in which the second stimulus was higher in pitch than the standard, and 3 tone pairs in which the second stimulus was lower in pitch. ISI and pair type (same–different) varied independently in pseudorandom order within each block. The intertrial interval within each block was 5 s. In the no-distraction condition, participants were instructed to watch the computer screen to see the first tone and second tone messages but were otherwise not required to perform any specific task. In the distraction task, participants were instructed to read single digits from a computer screen in their preferred language. Digits were presented at a rate of 1 per second.

Digit span. As a control condition, forward and backward digit span tests were administered to all participants. Participants were asked to repeat, either in the same or reversed order, sequences of digits read aloud at a rate of approximately 1 per second. Sequences were increased by a single digit after each correct response, and testing continued until participants made two successive errors at any particular level. The score for each participant was the greatest number of digits repeated correctly.

Data Analysis

Statistical analyses were performed with SPSS for Windows (SPSS, Chicago). Scores on the pitch discrimination study were analyzed via a repeated-measures ANOVA accounting for the between-subjects variable of diagnostic group (schizophrenic vs. nonschizophrenic) and the within-subject variable of distraction (with or without), pitch deviance (easy or difficult discrimination), and time (ISI range: 0 to 20 s). Multivariate F tests equivalent to Wilks's lambda were used to assess repeated measures effects of time. Post hoc contrast analyses of time effects were performed through profile analysis of parallelism (R. J. Harris, 1985). Performance on forward and backward digit span was assessed via one-way between-groups ANOVAs.

Results and Discussion

On the basis of prior studies, it was expected that both control and schizophrenic participants would show substantial decrements in tone matching performance, as indicated by a decreased percentage of correct identifications of similar and dissimilar tone pairs as a function of time between tones and between-tones pitch separation. This study was designed to determine whether schizophrenics (a) show impairments in working memory for tone matching, (b) show more rapid decay in performance over 0–20 s, and (c) are more influenced by decreases in between-tones pitch separation than controls. Visual inspection of the data (Figure 1) reveals that both groups performed at high levels in the no-delay conditions, indicating that the levels of Δf were sufficiently large to permit observation of

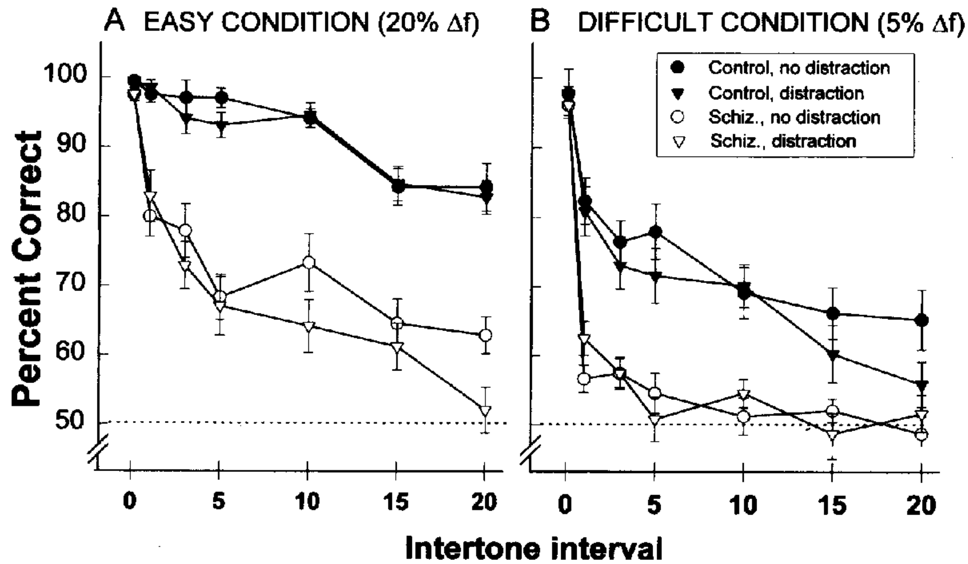

Figure 1. A: Tone matching performance for control and schizophrenic (schiz.) participants as a function of time between tones (interstimulus interval) during the easy discrimination condition (20% between-tones frequency difference [Δf]). The chance responding level (dashed line) is 50%. B: Tone matching performance during the difficult discrimination condition (5% between-tones frequency difference).

performance decay over time. Both groups also showed the expected exponential declines in performance to near chance (50% correct) levels as a function of time and between-tones pitch separation, indicating that the levels of Δf were sufficiently small that auditory sensory memory was required for task performance. Overall, tone matching performance was dramatically worse in schizophrenic participants than in controls at all intertone intervals of 1 s or greater. In both the easy and difficult conditions, the greatest relative performance decrements occurred between 0 and 1 s, the degree of impairment remaining reasonably stable thereafter.

Comparison of Overall Tone Matching Performance

To analyze the results statistically, we performed an ANOVA with the between-subjects variable of diagnostic group (control vs. schizophrenic) and the within-subject variables of time (0–20 s), degree of between-tones pitch separation (20% vs. 5% Δf), and presence or absence of visual distraction. Across conditions, there was a highly significant difference in performance between schizophrenic and control participants, $F(1, 33) = 50$, $p < .0001$, along with the expected highly significant effects of tone, $F(1, 33) = 115$, $p < .0001$, and time, $F(6, 28) = 88$, $p < .0001$. There was also a highly significant Tone × Time interaction, $F(6, 28) = 12$, $p < .0001$, indicating that, for both groups, the falloff in performance occurred more rapidly in the difficult discrimination condition than in the easy discrimination condition.

The Group × Tone interaction was nonsignificant, $F(1, 33) = 1.8$, *ns*, indicating that schizophrenic participants performed worse than controls in both the easy and difficult discrimination conditions and that the relative degree of decrement was similar in both conditions. There was, however, a highly significant Group × Time interaction, $F(6, 28) = 9.4$, $p < .0001$, indicating that performance fell off far more rapidly in schizophrenic participants than in control participants in both the easy and difficult discrimination conditions, especially between the 0-s and 1-s time period. There was also a significant three-way Group × Tone × Time interaction, $F(6, 28) = 3.4$, $p < .012$, reflecting the fact that the between-groups difference in falloff rate was somewhat more pronounced in the difficult discrimination condition than in the easy condition. Thus, during the easy discrimination task, the impairment for schizophrenic participants was most robust at ISIs of 3 s or greater. However, during the difficult discrimination task, performance differences between groups were greatest at the 1-s ISI, when schizophrenic individuals were performing just above chance level and control participants had not yet begun to exhibit significant decay of performance level.

There was no significant main effect of distraction, $F(1, 33) = 1.3$, *ns*, and no significant Distraction × Group interaction, $F(1, 33) = 0.0$, *ns*. There was, however, a significant Distraction × Time interaction, $F(6, 28) = 2.6$, $p < .04$, reflecting the fact that performance was worse in the distraction than in the no-distraction condition at the long ISI but not at the short ISI. There were no significant three-way interactions involving distraction. There was, however, a significant four-way interaction (Group × Time × Tone × Distraction), $F(6, 28) = 3.1$, $p < .018$, possibly reflecting the fact that the effects of distraction, which were apparent only at the long ISI, were most pronounced for the schizophrenic group in the easy condition and the control group in the difficult condition. Thus, at the 20-s ISI, schizophrenics performing the easy discrimination, paired $t(16) = 12$, $p < .0001$, and control participants performing the difficult discrimination, paired $t(14) = 9.0$, $p < .0001$, showed similar, highly significant decrements in performance as a function of distraction. Thus, the distraction effect emerged most strongly for each group when participants were in a sensitive range and not performing at floor or ceiling levels.

Comparison of Memory Retention Functions

The locus of the Group × Time interaction was investigated in two ways. First, performance decay rates were compared across groups within each difficulty condition. Second, decay rates were compared across difficulty conditions in which initial levels of delayed tone matching performance (1-s performance) were similar, that is, in the easy condition for schizophrenics and the difficult condition for controls.

When comparisons were conducted within conditions, schizophrenic participants experienced much more rapid performance decay during the 0–1-s period than did controls: easy, $t(33) = 5.7, p < .0001$, and difficult, $t(33) = 4.6, p < .0001$. In contrast, performance decay during the 1–10-s and 10–20-s periods was equivalent across groups in both the easy and difficult discrimination conditions. Thus, in comparisons conducted within condition, the deficit emerged in schizophrenic participants at the earliest delay time point and remained stable thereafter.

When the two groups were compared across levels of difficulty to equate for initial performance, no between-groups differences emerged (Figure 2). An ANOVA comparing performance of schizophrenics in the easy condition and controls in the difficult condition showed the expected significant effect of time, $F(6, 28) = 39.7, p < .0001$, but no significant effect of diagnostic group, $F(1, 33) = 0.1$, *ns*, or Group × Time interaction, $F(6, 28) = 1.9$, *ns*. Furthermore, the performance decay curves were strikingly similar for schizophrenic participants performing the easy condition and controls performing the difficult discrimination. This finding indicates that the auditory working memory performance of schizophrenics can be "normalized" by decreasing the difficulty of the discrimination to be made.

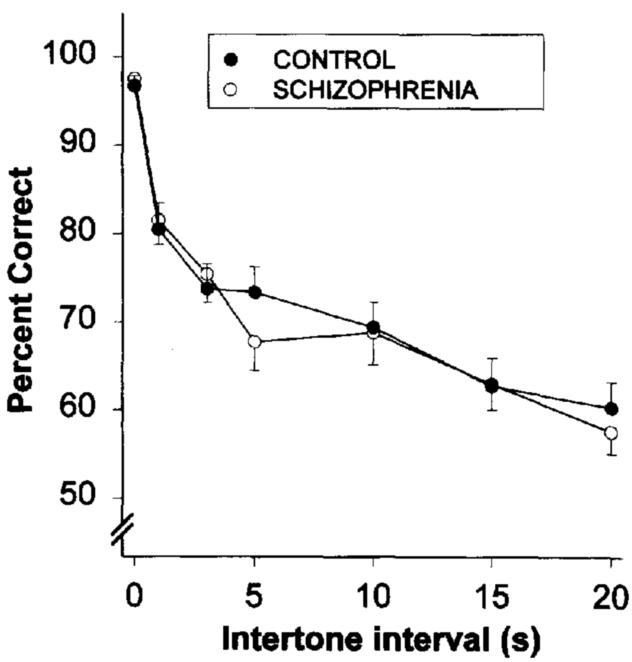

Figure 2. Tone matching performance for control participants in the difficult condition in comparison with schizophrenic participants in the easy condition, collapsed across presence or absence of visual distractors.

Signal Detection Analyses

To compare the response strategies of schizophrenic and control participants, we computed, two signal detection measures (Figure 3): A′, a nonparametric index of response sensitivity, and B″, a nonparametric index of response bias (Grier, 1971). These measures can be used under conditions when parametric measures (e.g., d′) are not appropriate. Data were collapsed across the 1–20-s delay interval to obtain sufficient data in each cell for estimating signal-detection theory-based performance indexes. Both A′ and B″ were subjected to an ANOVA with within-group variables of discrimination difficulty and distraction. There was a highly significant between-groups difference in sensitivity, $F(1, 32) = 48.3, p < .0001$, along with the expected decrease in response sensitivity in both groups as a function of increasing task difficulty, $F(1, 32) = 102.2, p < .0001$. There were no significant effects of distraction and no significant interactive effects. Schizophrenic participants in the easy condition performed at a level equivalent to that of controls in the difficult condition. Both groups showed positive response biases. Across conditions, there was a tendency for schizophrenic participants to show a less positive response bias, $F(1, 30) = 2.9, p = .1$, although there was a high degree of variability within each group. There were no effects of discrimination difficulty or distraction on response bias for either schizophrenic or control participants.

Digit Span

Forward and backward digit spans for control and schizophrenic participants were also determined as part of this study. These tasks require overall levels of sustained attention and cooperation similar to those involved in tone matching but do not depend on auditory sensory memory. There was no significant difference in digit span between schizophrenic and control participants. Schizophrenic participants scored 6.4 ± 0.2 digits forward and 4.3 ± 0.2 backward, as compared with 6.5 ± 0.1 forward and 4.4 ± 0.2 backward for control participants. Among schizophrenic participants, there were no correlations between neuroleptic–anticholinergic medication dose and performance on either tone matching or digit span tasks.

Overall, results of this experiment are twofold. First, schizophrenic participants showed a highly significant level of impairment in auditory sensory memory functioning. Second, the deficit was due primarily to a deficit in sensory memory precision, with little or no between-groups difference in maintenance of the sensory memory trace once allowance had been made for the deficit in precision. Effects of visual distraction were similar in each group, making it unlikely that differences in attentional processing were primarily responsible for the between-groups performance difference.

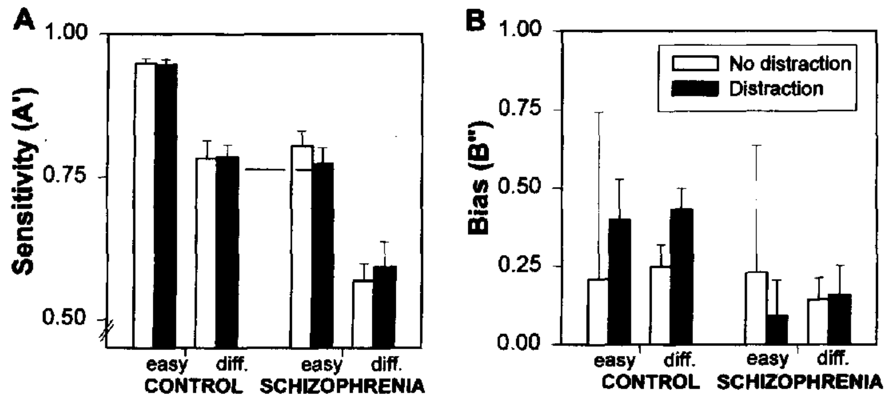

Figure 3. Grier's A′ and B″ measures of performance in the easy (20% frequency difference [Δf]) and difficult (diff.; 5% Δf) conditions in the presence and absence of visual distractors collapsed across 1–20-s interstimulus intervals. Under conditions in which the two groups showed similar levels of overall performance (see Figure 2), controls and schizophrenic participants also showed similar sensitivity (dashed line).

Experiment 2: No-Delay Tone Matching at Multiple Levels of Δf

In the previous experiment, levels of Δf were chosen to optimize detection of memory decay. As a consequence, performance at no delay was at near ceiling levels for both schizophrenic participants and controls, leaving unresolved the degree to which schizophrenia is associated with a deficit in no-delay performance. If no-delay performance truly is not impaired in schizophrenic patients, this would indicate that the problem is in retaining a sensory memory representation during the initial few hundred milliseconds of the intertone interval. However, if no-delay tone comparison performance is impaired, as is delayed tone comparison performance, this would suggest that the deficit in schizophrenic patients is in the precision of tone representation or the process of making a tone comparison rather than in the retention of sensory memory per se. To address this issue, we retested a subgroup of participants from Experiment 1 using a more extensive no-delay testing procedure optimized for detection of a between-groups difference in no-delay tone matching.

Stimuli consisted of composite tones similar to those used for no-delay testing in Experiment 1. Nine levels of Δf were used, including the no-difference (0% Δf) condition. To decrease overall task time, and because of the observation in Experiment 1 that the two groups used a similar response strategy (Figure 3), we presented stimuli equiprobably across Δf. Thus, as opposed to Experiment 1, in which 50% of stimuli were "same" (0% Δf), only 11% of the stimuli in Experiment 2 were 0% Δf, and the chance performance level was correspondingly reduced.

Method

Participants were 5 schizophrenics and 7 controls who took part in Experiment 1. Participants were selected on the basis of their continued availability for testing (i.e., they had either remained hospitalized or been readmitted) and continued willingness to participate. The final segment of each tone was either the same pitch as the initial segment or differed by a specific percentage (Δf). Nine levels of Δf were used: 0%, 1%, 1.5%, 2%, 2.5%, 3%, 5%, 10%, and 20%. Stimuli were presented in a single block of 64 trials incorporating eight presentations of each composite tone. Between-groups differences in no-delay performance were analyzed via an ANOVA with the within-group variable of Δf.

Results and Discussion

An initial analysis was performed to ensure that the 5 schizophrenic and 7 control participants recruited for retesting were representative of the initial sample in terms of both demographics and performance in the delayed tone matching paradigm (Experiment 1). The mean ages of the schizophrenic (35.4 ± 3.5 years) and control (35.3 ± 2.5 years) subgroups recruited for retesting were not significantly different from the mean ages of the original groups or from each other. The overall performance levels of subgroups recruited for retesting, moreover, were similar to those of the original schizophrenic and control groups as a whole. Despite the small size of the control and schizophrenic subgroups recruited for retesting, there was a highly significant, $F(1, 11) = 25$, $p = .001$, between-groups difference in delayed tone matching performance and a significant Group × Time interaction, $F(5, 6) = 7.2$, $p = .024$, similar to that found for the entire initial sample.

When no-delay performance for these participants was analyzed as a function of Δf (Figure 4), no significant between-groups difference in overall performance was observed, $F(1, 10) = 2.8$, $p = .13$. The Group × Δf interaction also did not reach statistical significance, $F(3, 8) = 0.8$, $p = .62$, although the effect of Δf, as expected, was highly significant, $F(3, 8) = 34$, $p = .007$. Inspection of the curve, however, revealed an apparent decrease in no-delay performance in a Δf range of 2.5%–10% caused by an apparent rightward shift of the performance versus Δf curve. When analyses were restricted to this range, a significant between-groups performance difference did emerge, $F(1, 10) = 9.5$, $p = .01$.

Neither controls nor schizophrenic participants showed ceiling-level responses in no-delay performance at 5% Δf in this

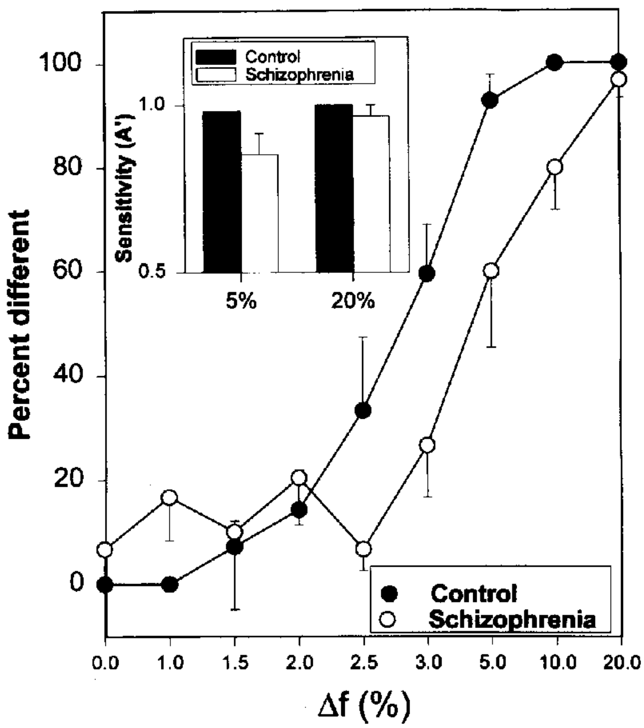

Figure 4. Performance of a subgroup of control (n = 7) and schizophrenic (n = 5) participants on no-delay tone matching at decreasing levels of between-tones pitch separation (Δf) in Experiment 2. Inset: Sensitivity (Grier's A') of control and schizophrenic participants to tone difference in the 5% and 20% Δf conditions.

experiment, in contrast to their performance in Experiment 1. Thus, both groups evidently experienced greater difficulty when varying levels of between-tones pitch separation were intermixed within a block than when pitches were segregated across blocks. Grier's A' analyses, performed as in Experiment 1 (Figure 4, inset), indicate that the deficit in no-delay performance, like the deficit in delayed tone matching performance, reflects an impairment of sensitivity to pitch difference among schizophrenic participants. Nevertheless, the sensitivity levels were substantially greater in the no-delay condition than in the delay conditions at equivalent Δf.

The major finding of this experiment is that schizophrenic participants do, in fact, show a deficit in no-delay tone matching relative to controls when the task is made sufficiently difficult. The deficit manifests itself as a rightward shift in the accuracy versus Δf response curve (Figure 4), indicating that schizophrenic participants encode or use pitch information less precisely than controls even in the no-delay task. In the no-delay condition, as well as in the delay condition, schizophrenic participants performing a 20% Δf discrimination were as accurate as controls performing a 5% Δf discrimination, although both groups were near ceiling in performance. These findings are consistent, therefore, with the findings from Experiment 1 showing decreased precision of encoding or trace use in delayed tone matching performance.

General Discussion

The concept that schizophrenia is associated with disturbances in working memory performance is now widely accepted. The great majority of working memory studies in schizophrenia, however, use complex paradigms that have been developed specifically to require frontal lobe processing (Goldman-Rakic, 1994). It thus has not been determined whether working memory dysfunction in schizophrenia is confined to prefrontal components or whether it may be observed even in simpler forms of working memory. The present study differed from previous investigations of working memory in schizophrenia in that it tested one of the simplest components of the working memory system, that is, the auditory sensory or echoic system. The major findings of this study are that schizophrenics show severe and robust impairments in an auditory sensory (echoic) memory task and that the deficits are apparent even at the shortest ISIs tested (Figure 1). However, when groups were matched for their performance at a short ISI, their performance levels remained comparable for the remainder of the test interval (Figure 2). These findings indicate, first, that working memory is impaired in schizophrenia even in tasks that require little high-order cognitive processing and, second, that the deficit reflects an impairment in the precision with which schizophrenics encode the physical properties of stimuli or use the encoded traces rather than the degree to which they are able to maintain the traces once the traces are established.

Impaired precision of the auditory memory system could potentially result from two distinct types of abnormality. It is possible that the representation of the physical properties of the first stimulus is encoded less precisely or less powerfully in schizophrenic than in control participants. Alternately, schizophrenic participants could be impaired in their ability to use working memory traces to make the same–different determination. Thus, even if the traces were encoded as powerfully and precisely as in controls, a larger difference between the presented tone and the stored stimulus representation might be required for schizophrenic patients to make the determination that a between-tones difference has occurred. Two distinct processes may be responsible for a same–different determination. First, neuronal ensembles residing within auditory cortex must compare the test tone with a locally maintained representation of the reference tone and determine the degree of match or mismatch. Second, the information resulting from the local comparison must be transferred to higher cortical areas where the appropriate response is selected. The deficit in tone matching could potentially reflect dysfunction either at the level of match–mismatch detection or response selection. Combined with electrophysiological studies showing impaired processing in schizophrenia at the level of auditory cortex (see later discussion), the most likely locus for the brain deficit underlying this abnormality is either at the level of the tone comparator within auditory cortex or at the level of information transfer from auditory cortex to higher cortical regions. A deficit similar to the one detected here would also occur if percepts in schizophrenia were inherently "noisier" than in controls, leading to impaired detectability of "signal." In any of these cases, the second tone would be considered erroneously as falling within the tonal range of the first, leading to a greater number of false-negative responses. Schizophrenic participants also show decreased sensitivity in no-delay tone matching relative to controls (Figure 4), supporting the concept that the deficit in schizophrenia affects primarily the tone matching process rather than retention of information.

As compared with other neurocognitive deficits in schizophrenia that localize to higher order association cortices in prefrontal or mesial temporal brain regions, the critical substrates for auditory working memory appear to reside within auditory sensory regions. After lesions of auditory regions, monkeys show an impaired ability to perform a tone matching task similar to that used in the present study (Colombo, D'Amato, Rodman, & Gross, 1990; Massopust, Wolin, & Frost, 1971). Similarly, in participants who had undergone surgical treatment for relief of intractable epilepsy, excisions that affected either the left or right Heschl's gyrus led to severe deficits in auditory working memory, whereas excisions that spared Heschl's gyri were without significant effect on simple pitch discrimination (Zatorre, 1985). Other brain regions appear to participate in auditory discrimination performance only when the underlying task or tonal stimuli become more complex. Thus, participants with right prefrontal lesions show greater sensitivity to the presence of auditory distractors than those with lesions elsewhere, but they show no deficit in performance in the absence of auditory distractors (Zatorre & Samson, 1991). Lesions of the right temporal lobe impair performance on melodic discrimination but do not affect matching of simple tones (Zatorre, 1985). HM, who underwent bilateral removal of mesial parts of the temporal lobe, including the hippocampus, became unable to enter auditory information into long-term memory stores but exhibited a normal decay curve over 7 s for a tone comparison test (Wickelgren, 1968). The deficit in auditory sensory memory in schizophrenia therefore cannot be attributed solely to dysfunction at the level of prefrontal cortex or hippocampus and suggests that working memory is impaired in schizophrenia even at the level of auditory sensory cortex.

The present study supports recent electrophysiological research reporting impaired generation of mismatch negativity (MMN) in schizophrenia. MMN is a short-latency cognitive event-related potential component that is elicited by physically deviant stimuli in an auditory "oddball" paradigm. MMN represents the outcome of an automatic process that compares each presented stimulus with a mnemonic trace encoding auditory experience over the preceding 10–20 s. MMN thus can be observed even in the absence of focused attention and in the presence of complex visual distractor tasks (Naatanen, 1990, 1992; Ritter, Deacon, Gomes, Javitt, & Vaughan, 1995). The MMN and auditory sensory memory traces have similar critical periods of duration and similar susceptibilities to forward and backward masking (Winkler, Paavilainen, & Naatanen, 1992; Winkler, Reinikainen, & Naatanen, 1993), indicating that MMN may index the operation of the brain auditory sensory memory system. Generators of MMN have been localized to the vicinity of primary auditory cortex via electroencephalograph and magnetoencephalography dipole mapping in humans (Hari, Hamalainen, & Ilmoniemi, 1984; Scherg, Vajsar, & Picton, 1989) and intracortical recordings in monkeys (Javitt, Schroeder, et al., 1995). Several recent studies have demonstrated impaired MMN generation in schizophrenia (Catts et al., 1995; Javitt, Doneshka, Grochowski, & Ritter, 1995; Javitt, Doneshka, Zylberman, Ritter, & Vaughan, 1993; Javitt, Schroeder, et al., 1995; Shelley et al., 1991), reflecting neurophysiological dysfunction at the level of primary auditory cortex (Javitt, Schroeder, et al., 1995). The present study is compatible with the hypothesis that the decreased MMN amplitude in schizophrenia reflects dysfunction of underlying auditory sensory memory processes.

Although schizophrenia is widely believed to be associated with disturbances in attention, it is unlikely that attentional dysfunction is the primary cause of the tone matching deficits observed here. Attention does not appear to be a major determinant of auditory sensory memory precision (Keller et al., 1995; Massaro & Kahn, 1973; Massaro & Warner, 1977), especially at short ISIs. Furthermore, in the present study, performance decrements due to distraction were strikingly similar for control and schizophrenic participants. It is also unlikely that disturbances in hearing acuity were responsible for the between-groups differences in tone matching performance. First, hearing was normal on a brief test before the main experiment of the present study. Second, several controlled studies have demonstrated that schizophrenic participants, as a group, do not show decreased auditory sensitivity relative to age-matched controls (Bartlett, 1935; Bruder, Spring, Yozawitz, & Sutton, 1980; Ludwig, Wood, & Downs, 1962). Finally, it is unlikely that the present findings are part of a nonspecific, "generalized" deficit (Chapman & Chapman, 1978). Although schizophrenic participants were impaired at all time intervals between 1 and 20 s, their retention rates were similar to those of controls when their performance was matched for 1-s performance. Moreover, schizophrenic participants showed greater falloff in performance than controls only in the 0–1-s period. During the 1–20-s period, retention rates were not different between schizophrenic and control participants. A generalized deficit would lead not only to poor initial performance but also to premature decay, even after control for initial performance, and would predict a more rapid falloff in performance across all time points.

A limitation of the present study is that participants were not individually matched for performance at 1 s before determination of decay curves. Instead, the experimental design used discrete levels of Δf that, it was hoped, would lead to equivalent performance levels when participants were compared across task difficulty levels. As such, the results of this experiment need to be confirmed in an independent cohort. An explicit prediction of this study was that if difficulty of the task were increased for controls (e.g., 2.5% Δf), their performance decay curves would resemble those of schizophrenic participants performing the 5% Δf discrimination. In contrast, if the task were made easier for schizophrenic participants (e.g., 40% Δf), their performance would resemble that of controls performing the 20% Δf discrimination. Across all levels of Δf, it was predicted that if groups were matched for performance at 1-s delay, they would perform equivalently over the ensuing 10–20 s. Two other limitations of the present study must also be addressed in future investigations. First, no participants with diagnoses other than chronic schizophrenia were studied. Thus, this study did not address the degree to which impaired encoding is limited to schizophrenia. Second, all schizophrenic participants included in this study were on antipsychotic medication at the time of testing, and several were also receiving anticholinergics. Although there were no correlations between performance and dose of either antipsychotic or anticholinergic medications, the possibility that the encoding deficit in schizophrenics is contributed to by medication cannot be excluded.

In summary, schizophrenic participants perform poorly on a large variety of complex neuropsychological tests. A goal of recent neuropsychological studies has been to define the simplest tasks on which performance is impaired so as to determine fundamental mechanisms underlying neurocognitive dysfunction in schizophrenia. The present paradigm, in which two tones must be compared after a brief delay, is among the simplest possible tests of working memory. Nevertheless, schizophrenic participants performed as poorly on this simple test of working memory as they do on more complex tests, such as the Wisconsin Card Sorting Test (Blanchard & Neale, 1994). The present study thus adds to prior research by demonstrating that the working memory deficit affects even sensory components of working memory. Finally, the present study suggests that the deficit in performance results from impaired precision of the auditory sensory memory system rather than from impaired retention of information. The present study, therefore, raises the possibility that a deficit in precision, rather than retention, may also underlie impaired performance on tasks requiring more complex, attention-dependent components of working memory.

References

American Psychiatric Association. (1987). *Diagnostic and statistical manual of mental disorders* (Rev. 3rd ed.). Washington, DC: Author.

Ammons, R. B., & Ammons, C. H. (1962). The Quick Test (QT) provisional manual. *Psychological Reports, 11,* 111–162.

Baddeley, A. D. (1986). *Working memory.* New York: Clarendon Press.

Baddeley, A. D. (1992). Working memory. *Science, 255,* 556–559.

Bartlett, M. R. (1935). The sensory acuity of psychopathic individuals. *Psychiatric Quarterly, 9,* 422–425.

Berliner, J. E., & Durlach, N. I. (1973). Intensity perception: IV. Resolution in roving-level discrimination. *Journal of the Acoustical Society of America, 53,* 1270–1287.

Blanchard, J. J., & Neale, J. M. (1994). The neuropsychological signature of schizophrenia; generalized or differential deficit. *American Journal of Psychiatry, 151,* 40–48.

Broadbent, D. E. (1958). *Perception and communication.* New York: Pergamon Press.

Bruder, G., Spring, B., Yozawitz, A., & Sutton, S. (1980). Auditory sensitivity in psychiatric patients and non-patients: Monotic click detection. *Psychological Medicine, 10,* 133–138.

Catts, S. V., Shelley, A. M., Ward, P. B., Liebert, B., McConaghy, N., Andrews, S., & Michie, P. T. (1995). Brain potential evidence for an auditory sensory memory deficit in schizophrenia. *American Journal of Psychiatry, 152,* 213–219.

Chapman, L. J., & Chapman, J. P. (1978). The measurement of differential deficit. *Journal of Psychiatric Research, 14,* 303–311.

Cohen, J. D., & Servan-Schreiber, D. (1993). A theory of dopamine function and its role in cognitive deficits in schizophrenia. *Schizophrenia Bulletin, 19,* 85–104.

Colombo, M., D'Amato, M. R., Rodman, H. R., & Gross, C. G. (1990). Auditory association cortex lesions impair auditory short term memory in monkeys. *Science, 247,* 336–338.

Cowan, N. (1984). On short and long auditory stores. *Psychological Bulletin, 96,* 341–370.

Cowan, N. (1988). Evolving conceptions of memory storage, selective attention and their mutual constraints within the human information processing system. *Psychological Bulletin, 104,* 163–191.

Cowan, N., Lichty, W., & Grove, T. R. (1990). Properties of memory for unattended spoken syllables. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 16,* 258–269.

Cowan, N., Winkler, I., Teder, W., & Naatanen, R. (1993). Memory prerequisites of mismatch negativity in the auditory event-related potential (ERP). *Journal of Experimental Psychology: Learning, Memory, and Cognition, 19,* 909–921.

Crowder, R. G. (1982). Decay of auditory memory in vowel discrimination. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 8,* 153–162.

Deutsch, D. (1970). Tones and numbers: Specificity of interference in immediate memory. *Science, 168,* 1604–1605.

Eriksen, C. W., & Johnson, H. J. (1964). Storage and decay characteristics of nonattended auditory stimuli. *Journal of Experimental Psychology, 68,* 28–36.

Glucksberg, S., & Cowen, G. N., Jr. (1970). Memory for nonattended auditory material. *Cognitive Psychology, 1,* 149–156.

Goldman-Rakic, P. S. (1994). Working memory dysfunction in schizophrenia. *Journal of Neuropsychiatry and Clinical Neurosciences, 6,* 348–357.

Grier, J. B. (1971). Nonparametric indexes for sensitivity and bias: Computing formulas. *Psychological Bulletin, 75,* 424–429.

Hari, R., Hamalainen, M., & Ilmoniemi, R. (1984). Responses of the primary auditory cortex to pitch changes in a sequence of tone pips. Neuromagnetic recordings in man. *Neuroscience Letters, 50,* 127–132.

Harris, J. D. (1952). The decline of pitch discrimination with time. *Journal of Experimental Psychology, 43,* 96–99.

Harris, R. J. (1985). *A primer of multivariate statistics* (2nd ed.). Orlando, FL: Academic Press.

Javitt, D. C., Doneshka, P., Grochowski, S., & Ritter, W. (1995). Impaired mismatch negativity generation reflects widespread dysfunction of working memory in schizophrenia. *Archives of General Psychiatry, 52,* 550–558.

Javitt, D. C., Doneshka, P., Zylberman, I., Ritter, W., & Vaughan, H. G., Jr. (1993). Impairment of early cortical processing in schizophrenia: An event related potential confirmation study. *Biological Psychiatry, 33,* 513–519.

Javitt, D. C., Schroeder, C. E., Steinschneider, M., Arezzo, J. C., Ritter, W., & Vaughan, H. G., Jr. (1995). Cognitive event-related potentials in human and non-human primates: Implications for the PCP/NMDA model of schizophrenia. *Electroencephalography and Clinical Neurophysiology, Suppl. 44,* 161–175.

Keller, T. A., Cowan, N., & Saults, J. S. (1995). Can auditory memory for tone pitch be rehearsed? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21,* 635–645.

Kolb, B., & Whishaw, I. Q. (1983). Performance of schizophrenic patients on tests sensitive to left or right frontal, temporal, or parietal function in neurological patients. *Journal of Nervous and Mental Disease, 171,* 435–443.

Lu, Z. L., Williamson, S. J., & Kaufman, L. (1992). Behavioral lifetime of human auditory sensory memory predicted by physiological measures. *Science, 258,* 1668–1670.

Ludwig, A. M., Wood, B. S., & Downs, M. P. (1962). Auditory studies in schizophrenia. *American Journal of Psychiatry, 119,* 122–127.

Massaro, D. W. (1970a). Perceptual processes and forgetting in memory tasks. *Psychological Review, 77,* 557–567.

Massaro, D. W. (1970b). Retroactive interference in short-term recognition memory for pitch. *Journal of Experimental Psychology, 83,* 32–39.

Massaro, D. W., & Kahn, B. J. (1973). Effects of central processing on auditory recognition. *Journal of Experimental Psychology, 97,* 51–58.

Massaro, D. W., & Warner, D. S. (1977). Dividing attention between auditory and visual perception. *Perception and Psychophysics, 21,* 569–574.

Massopust, L. C., Jr., Wolin, L. R., & Frost, V. (1971). Frequency discrimination thresholds following auditory cortex ablations in the monkey. *Journal of Auditory Research, 11,* 227–233.

Moss, S. M., Myers, J. L., & Filmore, T. (1970). Short-term recognition memory of tones. *Perception and Psychophysics, 7,* 369–373.

Naatanen, R. (1990). The role of attention in auditory information processing as revealed by event-related potentials and other brain measures of cognitive function. *Behavioral and Brain Sciences, 31,* 201–288.

Naatanen, R. (1992). *Attention and brain function.* Hillsdale, NJ: Erlbaum.

Norman, D. A. (1969). Memory while shadowing. *Quarterly Journal of Experimental Psychology, 21,* 85–93.

Park, S., & Holzman, P. S. (1992). Schizophrenics show spatial working memory deficits. *Archives of General Psychiatry, 49,* 975–982.

Pechmann, T., & Mohr, G. (1992). Interference in memory for tonal pitch: Implications for a working memory model. *Memory & Cognition, 20,* 314–320.

Pisoni, D. B. (1973). Auditory and phonetic memory codes in the discrimination of consonants and vowels. *Perception and Psychophysics, 13,* 253–260.

Ritter, W., Deacon, D., Gomes, H., Javitt, D. C., & Vaughan, H. G., Jr. (1995). The mismatch negativity of event-related potentials as a probe of transient auditory memory: A review. *Ear and Hearing, 16,* 52–67.

Sams, M., Hari, R., Rif, J., & Knuutila, J. (1993). The human auditory sensory memory trace persists about 10 s: Neuromagnetic evidence. *Journal of Cognitive Neuroscience, 5,* 363–370.

Scherg, M., Vajsar, J., & Picton, T. W. (1989). A source analysis of the late human auditory evoked potentials. *Journal of Cognitive Neuroscience, 1,* 336–355.

Shelley, A. M., Ward, P. B., Catts, S. V., Michie, P. T., Andrews, S., & McConaghy, N. (1991). Mismatch negativity: An index of a preattentive processing deficit in schizophrenia. *Biological Psychiatry, 30,* 1059–1062.

Strauss, M. E. (1994). Olfactory memory deficits in schizophrenia: Differential deficit or psychometric artifact [Letter to the editor]. *Schizophrenia Research, 12,* 89–90.

Strous, R. D., Cowan, N., Ritter, W., & Javitt, D. C. (1995). Auditory sensory ("echoic") memory dysfunction in schizophrenia. *American Journal of Psychiatry, 152,* 1517–1519.

Weinberger, D. R., Berman, K. F., & Zec, R. F. (1986). Physiologic dysfunction of dorsolateral prefontal cortex in schizophrenia: I. Regional cerebral blood flow evidence. *Archives of General Psychiatry, 43,* 114–124.

Wickelgren, W. A. (1968). Sparing of short-term memory in an amnesic patient: Implications for strength theory of memory. *Neuropsychologia, 6,* 235–244.

Winkler, I., Paavilainen, P., & Naatanen, R. (1992). Can echoic memory store two traces simultaneously? A study of event related brain potentials. *Psychophysiology, 29,* 337–349.

Winkler, I., Reinikainen, K., & Naatanen, R. (1993). Event-related brain potentials reflect traces of echoic memory in humans. *Perception and Psychophysics, 53,* 443–449.

Zatorre, R. J. (1985). Discrimination and recognition of tonal melodies after unilateral cerebral excisions. *Neuropsychologia, 23,* 31–41.

Zatorre, R. J., & Samson, S. (1991). Role of the right temporal neocortex in retention of pitch in auditory short-term memory. *Brain, 114,* 2403–2417.

Received January 2, 1996
Revision received July 9, 1996
Accepted July 9, 1996 ■