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Reduced Right Hemisphere Activation in Severely Abused Violent Offenders During a Working Memory Task: An fMRI Study

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This study uses functional magnetic resonance imaging (fMRI) to address two important gaps in our knowledge of brain functioning and violence: (1) What are the brain correlates of adults in the community who have suffered severe physical abuse early in life and who go on to perpetrate serious violence in adulthood? (2) What characterizes those who experience severe physical abuse but who refrain from serious violence? Four groups of participants recruited from the community (controls, severe physical child abuse only, serious violence only, and severely abused, seriously violent offenders) underwent fMRI while performing a visual/verbal working memory task. Violent offenders who had suffered severe child abuse show reduced right hemisphere functioning, particularly in the right temporal cortex. Abused individuals who refrain from serious violence showed relatively lower left, but higher right, activation of the superior temporal gyrus. Abused individuals, irrespective of violence status, showed reduced cortical activation during the working memory task, especially in the left hemisphere. Brain deficits were independent of IQ, history of head injury, task performance, cognitive strategy, and mental activity during the control task. Findings constitute the first fMRI study of brain dysfunction in violent offenders, and indicate that initial right hemisphere dysfunction, when combined with the effects of severe early physical abuse, predisposes to serious violence but that relatively good right hemisphere functioning protects against violence in physically abused children. Aggr. Behav. 27:111–129, 2001.

Key words: **violence; physical abuse; functional magnetic resonance imaging; working memory; right hemisphere; frontal; temporal; occipital**

INTRODUCTION

While brain imaging research is beginning to build an important body of knowledge on brain mechanisms that are involved in predisposing to violence, there are three major gaps in knowl-

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edge in this field. First, to the authors' knowledge, nothing is known about brain functioning in noninstitutionalized adults in the community who perpetrate serious violence. Second, there appears to have been no published study on brain functioning that attempts to understand why some individuals who have experienced severe physical abuse early in childhood do not go on to perpetrate serious violence. Indeed, there appears to have been little or no biological research of any type on either of these issues. Third, there has, to our knowledge, been no prior functional magnetic resonance imaging (fMRI) study of any violent or antisocial group.

Two previous reviews of brain imaging findings on violence have both concluded that the majority of studies show either frontal or temporal lobe deficits [Henry and Moffitt, 1997; Raine, 1993]. Most of the structural studies using MRI and computerized tomography (CT) have implicated damage to the temporal lobe, while functional studies using single photon emission CT (SPECT) and positron emission tomography (PET) have reported both temporal and frontal lobe deficits.

Six recent analyses of antisocial/violent offenders not contained in these reviews have also observed significant group differences. Volkow et al. [1995], using PET in a nonactivation, eyes open, resting state, observed reduced glucose metabolism in both medial temporal and prefrontal regions in eight psychiatric patients (three with schizophrenia) with a history of violence. Kuruoglu et al. [1996], using SPECT in a resting state, found that 15 alcoholics with antisocial personality disorder showed significantly reduced frontal regional cerebral blood flow (rCBF) compared with four alcoholics with other personality disorders and 10 nonalcoholic controls. Seidenwurm et al. [1997], using PET in a nonactivation, eyes open, resting state, found a significant reduction in glucose metabolism in the medial temporal lobe in seven violent offenders (two schizophrenic) referred for forensic examination and suspected of organic brain disease. Intrator et al. [1997], using SPECT, showed that eight drug-abusing psychopaths compared with nine nonpsychopaths had increased rCBF bilaterally in frontotemporal regions during the processing of emotional words. Raine et al. [1997] found reduced prefrontal glucose metabolism in addition to subcortical and white-matter deficits in 41 murderers (six schizophrenic) using PET and a continuous performance activation task. Murderers lacking psychosocial deprivation (i.e., without extreme poverty, broken home, child abuse, parental criminality) were particularly likely to show prefrontal deficits [Raine et al., 1998]. Consequently, these recent studies tend to confirm the earlier findings of temporal and/or frontal lobe abnormalities in violent offenders, with five of the six showing reduced cortical functioning in violent offenders and one showing *increased* functioning in drug-abusing psychopaths who may or may not have also shown violent behavior.

All of the previously mentioned recent studies (in addition to all previous samples) were conducted on selected samples derived from psychiatric hospitals, prisons, or forensic settings, and many contained violent offenders who were also schizophrenic. Some studies have used activation tasks, whereas others have not. As argued by Volkow et al. [1995], discrepancies in whether temporal or frontal deficits are observed are likely to be a function of differences in both subject groups and experimental methods.

With respect to hemisphere differences, some research has shown that violent and antisocial behavior is characterized by left hemisphere dysfunction [Moffitt, 1990; Pine et al., 1997; Raine, 1993; Volavka, 1995; Volavka et al., 1997], although some studies fail to observe evidence for selective left hemisphere deficits [e.g., Raine et al., 1994; Tarter et al., 1985; Volkow et al., 1995]. Other research shows that right hemisphere dysfunction characterizes violent offenders. For example, violent sex offenders have been found to have a greater incidence of right temporal horn dilation (41%) compared with nonviolent sexual offenders (11%) and controls (13%) as measured by CT [Hucker et al., 1988]. Murderers have recently been shown to have more electroencephalographic (EEG) deficits (i.e., abnormalities in amplitude, coherence, and phase) in the right than the left hemisphere, with multiple abnormalities being especially present in the right temporal cortex [Evans and Park, 1997]. Neuropsychological data also suggest that psychopathic criminals may rely less on right hemisphere conative-emotional processes and more on left hemisphere denotive-linguistic processes [Day and Wong, 1996]. Latencies of event-related potentials (N100, P200, P300) have been found to be longer in the right hemispheres of violent criminals compared with nonviolent criminals and controls [Drake et al., 1988]. An intriguing case intervention demonstrated a reduction in both physical and verbal aggression in a schizophrenic when cognitive exercises were used to stimulate the right hemisphere but not when the left hemisphere was stimulated [Gale, 1990], suggesting that reduced right hemisphere functioning may relate to the expression of aggression. Given this body of findings, the current study set out to test whether right hemisphere deficits, especially in the right temporal cortex, are present in violent offenders in addition to left hemisphere dysfunction.

The relationship between physical child abuse and violence is well established [Lewis et al., 1988; Tarter et al., 1984; Widom, 1997]. In surprising contrast, there seems to be little or no research on factors that differentiate abused victims who go on to perpetrate violence from those who refrain from adult violence. From the standpoint of brain functioning, both groups may be expected to show evidence of left hemisphere dysfunction because structural MRI studies have shown volume reductions in the left mesial temporal cortex (specifically the hippocampus) in individuals who have suffered severe child abuse [Bremner et al., 1997; Stein et al., 1997], findings consistent with other neurophysiological (combined EEG, CT, and MRI) and neuropsychological data implicating selective deficits to the left hemisphere in abused individuals [Bremner et al., 1995; Ito et al., 1993; Raskin, 1997]. In addition to showing left hemisphere deficits (possibly consequent to abuse), violent abused individuals may have additional brain deficits (e.g., right hemisphere dysfunction or more severe/widespread left hemisphere dysfunction) that provide an additional, necessary predisposition toward adult violence. Conversely, abused individuals may refrain from violence in part because either they lack the preexisting biological predisposition to violence that characterizes abused violent individuals and/or they possess some biological factor (i.e., better functioning in another brain region) that protects them from violence outcome. The current study set out to provide initial data to help address these unexplored issues.

The current study also represents an attempt to address limitations of our previous work [Raine et al., 1994, 1997, 1998]. By using noninvasive fMRI (as opposed to PET) we were able to assess a less select community sample of nonschizophrenic violent offenders as opposed to a very select sample consisting of murderers pleading not guilty by reason of insanity, some of whom were schizophrenic [Raine et al., 1997]. By using a task that results in widespread bilateral activation as opposed to our previous use of the continuous performance task that was biased toward activating the right hemisphere [Buchsbaum et al., 1990], we are better able to assess bilateral hemisphere functioning. By using a specific measure of severe child abuse validated against prospective data, we were able to assess more specifically the moderating effect of early physical child abuse on violence–brain functioning relationships compared with the global measure of "psychosocial deprivation" that we had used previously.

METHOD

Participants

Male participants (N = 25) were recruited from temporary employment agencies in Los Angeles and hired to participate in a research study. Recruitment was centered on this population because pilot data had shown that this community group had relatively high rates of violence perpetration [Raine, A., et al., unpublished data, 1999]. Exclusion criteria consisted of age younger than 21 years or older than 45 years, nonfluency in English, a lifetime history of epilepsy and psychosis, inability to see small objects without the aid of spectacles from 25 ft, claustrophobia, pacemaker, and metal implants. Participants form part of a larger study on structural brain imaging deficits in offenders [Raine et al., 2000] and represent a subgroup on whom fMRI data were obtained. Full informed consent was obtained according to Institutional Review Board procedures at U.S.C.

Serious Self-Report Violence

A history of severe violence perpetration was derived using the self-report interview technique [Elliott et al., 1983; Klein, 1989]. The interview represented an adult extension of the self-report delinquency measure used in the National Youth Survey [Elliott et al., 1983] and included 44 crimes ranging from minor theft to murder. Official measures of violence (police arrests, court convictions) are seriously biased in that they only capture the unsuccessful offender who is very unrepresentative of the larger sample of offenders [Moffitt, 1996]. Furthermore, caught criminals have been found to commit many more offenses than they were ever arrested for [Blumstein et al., 1986]. In contrast, self-report measures encapsulate the full spectrum of offending and have been shown to have good internal reliability, test-retest reliability, predictive validity, and external validity and have the significant advantage of identifying the uncaught offender [Elliott et al., 1983; Farrington, 1989; Huizinga and Elliott, 1986; Klein, 1989; Moffitt, 1996].

Set against these advantages of self-report methods are two potential disadvantages. First, while false positives are not likely, false negatives (denial of violence by truly violent offenders) present a more serious problem. Second, the definition of violence in some previous self-report studies has been too lax, including minor, inconsequential assaults.

An attempt to minimize the first disadvantage was made by obtaining a certificate of confidentiality from the Secretary of Health that protected the research investigators under section 303 (a) of the Public Health Act 42 from being subpoenaed by any federal, state, or local court in the U.S. to release the self-report crime data. Consequently, participants were protected from the possible legal action that could be taken against them for crimes they committed and admitted in interview but that were not detected and punished by the criminal justice system.

To help address the second criticism, violence was limited to serious forms of violence that either caused bodily injury or trauma or were life-threatening acts. Eight items fit this definition: attack on spouse or girlfriend causing bruises or bleeding, attack on relative/friend causing bruises or bleeding, attack on stranger causing bruises or bleeding, rape, using a weapon in a fight, using force or a weapon to rob, firing a gun at someone, and attempted murder/murder. Nine of the 23 subjects (39%) were classified as serious violent offenders.

Severe Physical Abuse in Childhood

A major limitation of retrospective accounts of child abuse until recently is that they have not been validated against prospectively collected official reports of childhood victimization. The exception is a recently developed self-report interview measure based on a modification of the Conflict Tactics Scale (CTS) [Straus, 1979] and validated against adults who had been physically abused 20 years previously as demonstrated by official court reports of child abuse [Widom and Shepard, 1996]. The instrument showed good discriminant and predictive validity [Widom and Shepard, 1996]. This scale was administered to participants, and dichotomous summary subscale scores (reasoning, verbal aggression, minor violence, severe violence, and very severe violence) were computed according to Straus and Gelles [1990]. While the strength of this measure lies in its previous validation against prospective data, false negatives remain a problem for all retrospective measures of physical abuse.

Abuse was restricted to acts occurring before the end of elementary school because it is thought that early trauma may be of particular importance in influencing brain and behavioral development [Teicher et al., 1997]. Furthermore, abuse was defined using the most extreme ("very severe abuse") subscale of the CTS that showed the best discriminant validity, lowest false positives, and highest true negatives of the CTS subscales [Straus and Gelles, 1990]. This subscale consisted of the following items: "kick, bite, or hit you with a fist," "beat you up," "burn or scald you," "threaten you with a knife," or "use a knife or gun." Ten of the 23 participants (43%) had a history of very severe physical abuse in early childhood.

Categorization Into Violence-Abuse Subgroups

One subject had missing data on violence perpetration and child abuse, and one subject was excluded a priori due to a significant initial alignment error along the anterior commissure–posterior commissure (AC-PC) line in fMRI testing, leaving a final sample of 23. Four groups were formed based on the measures of serious violent offending and very severe physical child abuse: (1) Comparisons (no child abuse, no violence, n = 9), (2) Violent Only (violence but no child abuse, n = 4), (3) Abused Only (child abuse but no violence, n = 5), and (4) Violent Abused (child abuse and violent offending, n = 5).

Demographic and educational data were obtained from a demographic interview, and estimates of verbal, performance, and total IQ scores were obtained from four subtests (Vocabulary, Arithmetic, Block Design, Digit Symbol) of the WAIS-R [Wechsler, 1981]. Handedness was measured using the abbreviated Oldfield Inventory [Bryden, 1977], with high scores indicating a stronger preference for right-handedness. Parental occupation was rated on a 1 to 7 scale, with high scores indicating higher occupation [Hollingshead, 1975]. Demographic and cognitive characteristics of the four subject groups are given in Table I. There were no significant differences in age, ethnicity, parental occupation, years of education, estimated IQ, and handedness ($P > .10$).

Visual/Verbal Working Memory Task

Because our hypotheses were focused on group differences in activation of both left and right hemispheres, our goal was to develop a complex challenge task that would maximally activate both left and right hemispheres in frontal, temporal, and occipital regions. Visual and verbal

TABLE I. Means (SDs) and *P* Values for One-Way ANOVAs for Group Comparisons on Demographic, Cognitive, and Handedness Characteristics of the Four Groups

	Controls (n = 9)	Abused (n = 4)	Violent (n = 5)	Abused violent (n = 5)	F	*P*
Age	30.4 (6.2)	30.0 (11.5)	29.6 (7.0)	25.8 (4.6)	0.5	.69
Years of education	13.5 (1.6)	13.5 (1.9)	13.5 (1.0)	15.0 (2.2)	1.2	.34
Parental occupation	4.3 (1.6)	5.8 (2.3)	5.6 (2.2)	6.5 (1.8)	1.3	.31
Intelligence	96.4 (12.7)	87.0 (12.1)	109.8 (20.1)	106.2 (17.1)	2.1	.14
Handedness	34.7 (10.3)	34.3 (8.0)	31.6 (11.1)	33.8 (8.3)	0.1	.95
Ethnicity						
White	6	1	4	6	$\chi^2 = 5.4$	.14
Nonwhite	4	3	2	1		

working memory tasks have been found to activate a complex neurocognitive network of cortical regions, including frontal [Hinke et al., 1993; McCarthy et al., 1994], temporal [Faillenot et al., 1997; Pearlson, 1997], and occipital [Kraut et al., 1997; McIntosh et al., 1994] regions. Given recent findings showing deficits in working memory in abused individuals [Bremner et al., 1995] and deficits in executive functions and working memory in violent offenders [Seguin et al., 1995], we developed a visual/verbal working memory task to challenge widespread brain regions in participants.

Stimuli consisted of 262 different line drawings of familiar objects (e.g., candle, *bus*, cup, tree, nut, *bus*) that were presented sequentially at the fixation point in the middle of a black-and-white video monitor located 6 ft from the foot of the subject and viewed by the subject through prism glasses. The monitor was modified to reduce distortions in the picture caused by the main magnetic field. Objects were 6 inches in size and subtended a visual angle of 2.5°.

Each stimulus was presented for 1,545 msec. Each block consisted of 22 objects, with a duration of 34 sec. Within each block, there were always three repeated pairs of objects (e.g., *bus* in the previous example). The number of intervening objects between the repeats were varied randomly across the blocks. Each block of 22 objects (experimental condition) was followed by a control condition lasting 33 sec, during which subjects viewed a uniformly illuminated screen with a central fixation point. There were 12 blocks of the experimental condition and 12 blocks of the control condition (four experimental and four control blocks for each of the three axial slices). True positives, true negatives, false positives, false negatives, total correct, total error, d prime, and beta were calculated from behavioral responses to the stimuli.

Subjects were told that different objects would appear on the screen for about half a minute and that they should press a response button when they saw an object that had been previously presented in the same sequence. The screen would then go blank for about half a minute, during which they should fixate a dot in the center of the screen and try to keep their mind clear.

Competent task performance required the participant to maintain representations of visual stimuli in working memory until a repeat was detected. Because the stimuli were drawings of familiar, everyday objects, covert naming by the subjects was expected to take place (see Table IV). Consequently, this task contained multiple components of visuospatial and verbal information processing, which included object recognition, object naming, verbal working memory, visual working memory, and sustained attention.

Recognition Memory Task

After scanning procedures were complete, subjects participated in a recognition memory task. A subset of the objects presented during scanning together with objects never presented were shown to the subjects on a sheet of paper. Subjects were asked to select the items (both single presentations and repeat presentations) that they had seen during the scanning task. A total of 86 items were presented consisting of 10 repeats, 33 single presentations, and 43 never-presented objects. Number of true repeats, true single presentations, and false positives were derived from this task.

Task Strategy

To obtain some indication of the cognitive strategy employed by subjects during the visual/verbal working memory task, subjects answered two questions on a 5-point scale (1 = none, 5 = all) immediately after imaging regarding (1) the extent of covert naming of objects during the task and (2) the extent of verbal rehearsal.

Mental Activity During Control Task

To obtain some indication of the extent to which subjects engaged in varied forms of mental activity during the control task (fixating a dot on a blank screen), subjects answered four questions on a 5-point scale (1 = never, 5 = always) immediately after imaging regarding (1) daydreaming, (2) visualization of the objects, (3) covert naming of objects, and (4) other.

Imaging Procedures

A 1.5-T Philips MRI system with a standard head coil was used to acquire all images. Gradient-echo T2*-weighted images were acquired in a 128×256 matrix with TR = 52 msec, TE = 45 msec, flip angle = 45°, and with one average. A full time series of 44 images was acquired separately for each of three contiguous 8-mm-thick transaxial slices. The field-of-view was 24×24 cm, resulting in an in-plane (x,y) resolution of approximately 1×2 mm. Images were linearly interpolated onto a 256×256 grid before further processing.

Three contiguous slices were positioned with reference to the AC-PC line in the following manner: slice 1 encompassed the 8 mm of tissue immediately inferior to the AC-PC line (Talairach 9), slice 2 encompassed the 8 mm of tissue immediately superior to the AC-PC line (Talairach 8), and slice 3 encompassed the 8 mm of tissue immediately superior to slice 2 (Talairach 7-8). The three axial slices were positioned using a midsagittal scout image to locate the AC-PC plane. Head movement was minimized through the use of foam padding and the use of a head strap to restrain the participant. These slices were selected because pilot work showed that they produced maximal activation to this particular working memory task and also allowed assessment of partial areas of three lobes and two hemispheres.

During each 34-sec "on" block of experimental stimuli, five gradient-echo images were acquired. The "on" block was immediately followed by a 34-sec control block. Five gradient-echo images were also acquired during the control "off" period. There were a total of four "on" and four "off" periods per slice, resulting in the time series of 44 gradient-echo images per slice, including four prestimulus control images that were used to reach a steady state and that were later discarded.

Immediately after acquiring the functional data, structural images of the same three slices were acquired on a 256×256 grid using a multislice spin-echo sequence with TR = 350 msec, TE = 12 msec, flip angle = 90°, and one average. The in-plane resolution was 0.96×0.96 mm.

Image Analysis

Image processing. Prior to analysis, a 2D registration algorithm was used to compensate for both rigid body and nonrigid body head movement during data acquisition [Singh et al., 1996, 1998]. Activated voxels were identified by thresholding the linear correlation coefficient derived from a correlation of the time course of each voxel with a reference sine function [Bandettini et al., 1993; Singh et al., 1995]. The threshold was set to correspond to $P < .01$, $r = .40$). The sine function was delayed by one scan (6.8 sec) to compensate for hemodynamic lag time. The time course of each voxel was obtained from the series of gradient-echo images.

Even after registration, some movement artifacts, particularly those that may be correlated with task performance, remain and are usually seen as activated voxels on the border of the brain and ventricles [Kim et al., 1993]. In addition, pulsatile motion in the ventricles and large blood vessels can produce artifacts that appear as replications or "ghosts" of the moving structure along the phase-encoding (horizontal) axis in these images [Hu and Kim, 1994]. To minimize error from these artifacts, two trained independent raters (blind to each others' ratings and to group membership) excluded voxel clusters from each slice that were deemed to be a function of these artifacts. The intraclass correlation [McGraw and Wong, 1996] for interrater agreement for artifact identification was .99.

Cluster-size threshold. The major problem of multiple statistical comparisons in identifying areas of brain activation is often dealt with by the use of Bonferroni corrections [e.g., Worsley et al., 1992]. While reducing type 1 errors, this technique results in a considerable loss of statistical power. An alternative approach, outlined by Forman et al. [1995], is the use of a cluster-size threshold to reject false positives. This approach assumes that areas of true activation stimulate signal changes over several contiguous voxels. In this study, we defined true activation as four or more immediately neighboring voxels [Lang et al., 1998; Shaywitz et al., 1995].

Localization and quantification of voxels. Functional images were overlaid on the corresponding structural images to identify the locus of activation. Quantitative counts of voxels exceeding cluster-size threshold were conducted by two raters blind to group membership and each other's ratings. Total voxel counts were made for six regions (three in each hemisphere): (1) frontal cortex, (2) temporal cortex, and (3) occipital cortex. Using an MRI atlas as reference [Talairach and Tournoux, 1988], landmarks were identified to delineate the three lobes and included the genu of the corpus callosum, the lateral sulcus, the anterior aspect of the insula, and the sulcal boundary between Brodmann areas 37 and 19. Interrater agreement (blind to each other's assessments) for these anatomical landmarks was 87.3%, with disagreements decided by consensus. Left vs. right hemisphere identification was made with reference to the longitudinal fissure.

RESULTS

Data were square-root transformed to help normalize distributions and were analyzed using a five-way 3 × 3 × 2 × 2 × 2 (Lobe × Slice × Hemisphere × Violence × Abuse) repeated-measures multivariate analysis of variance (ANOVA) [SPSS, 1997]. The main effects and interactions involving Hemisphere, Lobe, and Slice that assess the effects of the challenge task on brain activation are first reported, followed by results on interactions with the two between-group factors (Violence and Abuse). Effect sizes were calculated and reported as Cohen's d [Cohen, 1988].

Effects of Challenge Task on Brain Activation

Means and SDs for number of activated voxels by Lobe, Slice, and Hemisphere are given in Table II. There was a significant effect of Lobe, $F(2,18) = 6.1$, $P < .01$, d = 1.64. Paired *t*-tests indicated that prefrontal cortex showed significantly more activation than both temporal ($P < .006$, d = 0.54) and occipital ($P < .001$, d = 1.01) regions, with temporal cortex also showing significantly greater activation than occipital cortex ($P < .04$, d = 0.64).

There was a significant Lobe × Slice interaction, $F(4,16) = 6.3$, $P < .003$, d = 2.49. Paired *t*-tests were used to break down the interaction (within-slice lobe comparisons). Differences between lobes were greater at the more superior slices. Specifically, the frontal lobes did not differ significantly from temporal and occipital lobes at the more inferior slice 1 ($P > .12$), and the middle slice 2 ($P > .06$), but showed significantly more activation than temporal ($P < .0001$, d = 1.29) and occipital ($P < .0001$, d = 1.18) lobes at the superior slice 3. Conversely, temporal cortex showed greater activation than occipital cortex at slice 1 ($P < .02$, d = 0.41) and slice 2 ($P < .03$, d = 0.59).

There was a significant Lobe × Slice × Hemisphere interaction, $F(4,16) = 3.6$, $P < .03$, d = 1.90, indicating that the previous Lobe × Slice interaction was a function of Hemisphere. Specifically, in the left hemisphere, frontal cortex was maximally activated at the more superior

TABLE II. Means (SDs) for Number of Activated Voxels (Square Root Transformed) by Lobe, Hemisphere, and Slice

	Left hemisphere	Right hemisphere	Total brain
Frontal			
Slice 1	3.2 (3.1)	3.2 (2.6)	6.4 (4.8)
Slice 2	3.4 (3.2)	4.9 (3.6)	8.3 (6.1)
Slice 3	4.9 (3.7)	5.5 (2.9)	10.4 (5.8)
Total	12.2 (8.5)	13.7 (7.1)	25.1 (13.9)
Temporal			
Slice 1	3.2 (1.9)	3.6 (2.6)	6.1 (3.7)
Slice 2	4.2 (2.6)	3.3 (2.3)	7.5 (3.8)
Slice 3	2.0 (2.6)	2.4 (2.1)	4.4 (3.5)
Total	9.7 (5.4)	9.2 (5.1)	19.0 (8.5)
Occipital			
Slice 1	2.2 (2.2)	2.4 (2.2)	4.6 (3.6)
Slice 2	2.5 (2.4)	2.7 (2.4)	5.2 (4.0)
Slice 3	2.6 (2.4)	2.2 (2.4)	4.7 (3.9)
Total	7.4 (4.9)	6.8 (4.7)	14.2 (7.7)

slice 3, differing significantly from temporal ($P < .001$, d = 0.92) and occipital ($P < .008$, d = 0.75) cortex at this level. Conversely, temporal cortex was maximally activated, and at a significantly higher level, than occipital cortex at the middle slice 2 ($P < .007$, d = 0.68).

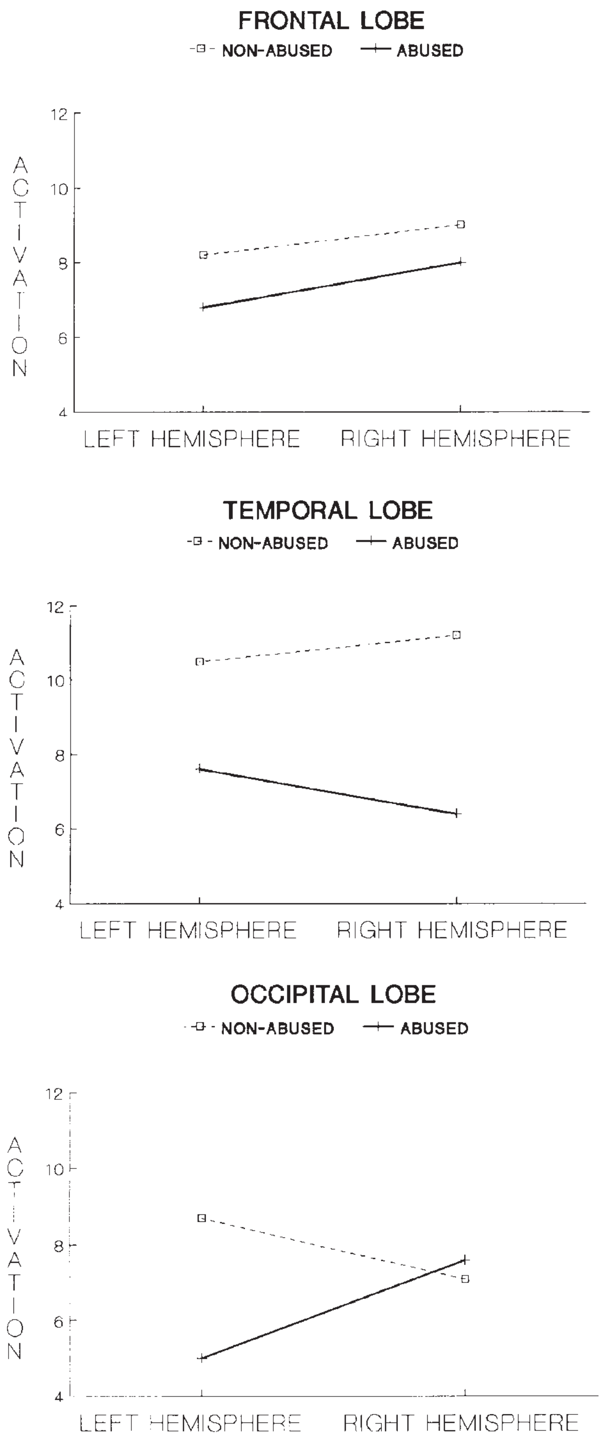
For the right hemisphere, frontal cortex was maximally activated at both slices 2 and 3, differing significantly from temporal ($P < .05$, d = 0.54) and occipital ($P < .04$, d = 0.73) cortex at the middle slice 2, and differing significantly from temporal ($P < .0001$, d = 1.24) and occipital ($P < .0001$, d = 1.25) cortex at the superior slice 3. Conversely, temporal cortex differed significantly from occipital cortex at the inferior slice 1 only ($P < .03$, d = 0.51).

All other main effects and interactions involving slice, lobe, and hemisphere were nonsignificant ($P > .07$).

Group Differences on Task Activation

The repeated-measures multivariate ANOVA indicated no main effect of Violence, $F(1,19) = 0.2$, $P > .64$, d = 0.20, or Abuse, $F(1,19) = 2.4$, $P > .13$, d = 0.70, but did show a significant Abuse × Lobe × Hemisphere interaction, $F(2,18) = 5.0$, $P < .02$, d = 1.50. A breakdown of this interaction is shown in Figure 1 and illustrates that while in the left hemisphere Abuse was associated with reduced functioning in all lobes, in the right hemisphere it was associated with frontal and temporal lobe reductions but not occipital reductions. Furthermore, the decrement for Abuse appeared maximal in temporal cortex.

A significant Violence × Abuse × Hemisphere interaction, $F(1,19) = 9.5$, $P < .006$, d = 1.38, was also obtained. This three-way interaction is illustrated in Figure 2, which shows left and right hemisphere functioning for each of the four participant groups. The interaction indicated differential activation of left and right hemispheres in the Violent Abused and Abused Only groups. The Violent Abused group showed the lowest level of right hemisphere functioning and the second lowest level of left hemisphere functioning. Conversely, the Abused Only group showed the lowest level of left hemisphere functioning but were equivalent to the Controls on right hemisphere functioning. A contrast comparing the Violent Abused group with all other groups showed the Abused Violent group to have significantly lower right hemisphere functioning ($t = 3.8$, $P < .001$, d = 1.92). A contrast comparing the Abused Only group with all other


FRONTAL LOBE
NON-ABUSED
ABUSED
ACTIVATION
12
10
8
6
4
LEFT HEMISPHERE
RIGHT HEMISPHERE
TEMPORAL LOBE
NON-ABUSED
ABUSED
ACTIVATION
12
10
8
6
4
LEFT HEMISPHERE
RIGHT HEMISPHERE
OCCIPITAL LOBE
NON-ABUSED
ABUSED
ACTIVATION
12
10
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LEFT HEMISPHERE
RIGHT HEMISPHERE

Fig. 1.

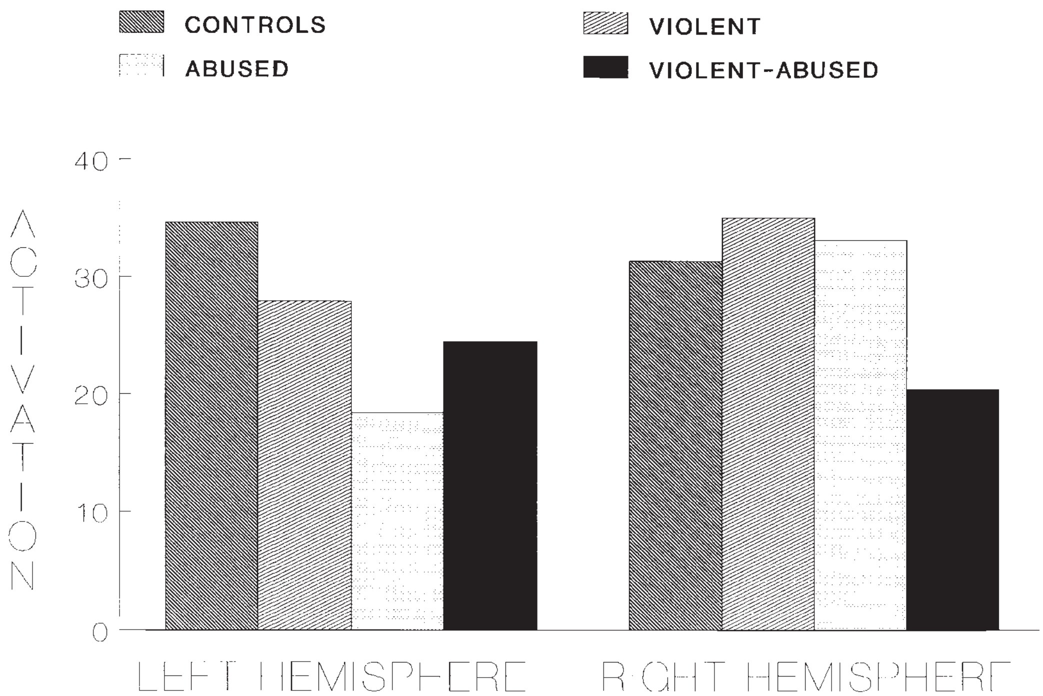

Fig. 2. The Violence × Abuse × Hemisphere interaction showing low right hemisphere functioning in the Violent Abused group and low left hemisphere functioning in the Abused Only group. Activation is the square root of number of activated voxels above cluster threshold level.

groups on left hemisphere functioning, however, failed to reach statistical significance ($t = 1.6$, $P > .13$, d = 0.81). Examples of functional activation in Controls, Abused, and Violent Abused are shown in Figure 3.

There was a trend toward both a Violence × Lobe × Hemisphere interaction, $F(2,18) = 3.2$, $P < .07$, d = 1.20, and also a Violence × Abuse × Lobe × Hemisphere interaction, $F(2,18) = 3.1$, $P < .07$, d = 1.19, which suggested that the above group differences in hemispheric functioning may be a function of cortical lobe. Because (1) previous research reviewed previously showed localization of deficits in violent offenders to temporal and frontal brain areas and deficits in the left temporal lobe in abused individuals, (2) there were two similar trends involving lobes and hemispheres in conjunction with groups, and (3) effect sizes were large, exceeding 1.0, further analyses were conducted to break down the more complex four-way trend. The Violent Abused group had a substantial and significant reduction in right temporal lobe functioning compared with the other groups combined (M = 2.8 vs. 11.1, respectively, SD = 2.9 vs. 4.2, $t = 4.1$, $P < .001$, d = 2.07). The Abused group instead showed a trend toward poorer left temporal functioning compared with the other three groups (M = 5.8 vs. 10.1, SD = 3.8 vs. 4.7, $t = 1.8$, $P < .09$, d = 0.91), which was carried by a significant reduction in the most superior (3) slice correspond-

Fig. 1. The Abuse × Lobe × Hemisphere interaction illustrating reduced functioning in the Abused compared with non-Abused group except for the right occipital region. Activation is the square root of number of activated voxels above cluster threshold level.

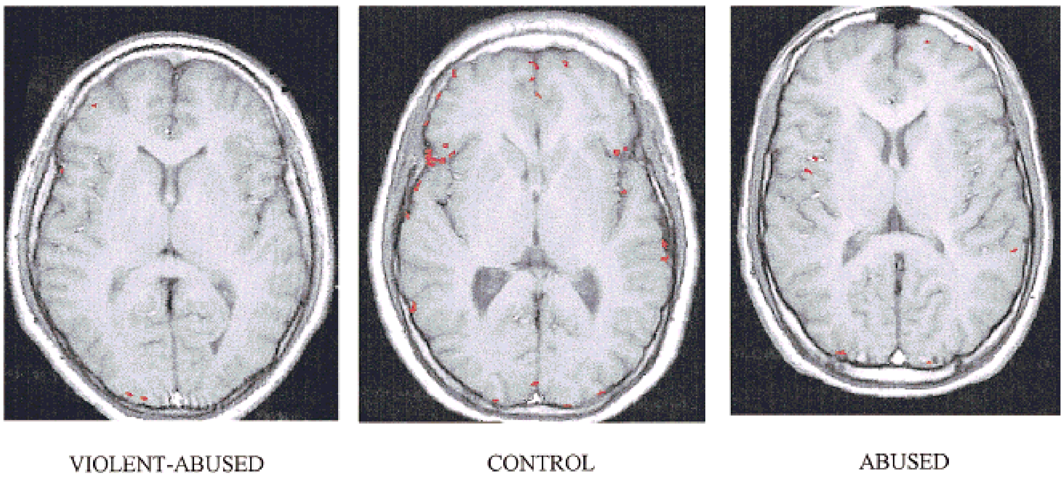

Fig. 3. Examples of artifact-free activation to the working memory task in one Violent Abused participant, one Control, and one Abused Only participant. Right and left are reversed. While the Control subject shows clustering of pixels in the frontal and temporal cortices bilaterally, the Violent Abused participant shows little activation in either hemisphere, while the Abused Only subject shows some activation in the right hemisphere with largely artifact, noise, and single voxel activation in the left hemisphere.

ing to the superior temporal gyrus (M = 0.5 vs. 2.3, SD = 1.0 vs. 2.7, $t = 2.3$, $P < .04$, d = 1.16). In contrast, the Abused group showed significantly *greater* activation in the right superior temporal gyrus (M = 4.6 vs. 2.0, SD = 1.6 vs. 1.9, $t = 2.6$, $P < .02$, d = 1.31).

Potential Confounds

Potential effect of history of head injury. It is possible that head injuries could contribute to the brain dysfunction observed in the Abused and Violent Abused groups. Regarding number of times the participant had been concussed, there were no significant group differences, $\chi^2 = 3.0$, df = 6, $P > .81$, with rates of concussion being 33% for Controls, 29% for Violent Only, 0% for Abused Only, and 20% for Abused Violent. Similarly, regarding hospitalization for head injury (irrespective of suffering concussion), there were no significant group differences, $\chi^2 = 2.8$, df = 3, $P > .42$, with 56% of Controls being hospitalized compared with 25% for Violence Only, 25% for Abused Only, and 60% for Violent Abused. Consequently, it does not appear that the functional deficits in the Abused Only and Violent Abused groups can be explained by physical trauma resulting from a history of head injuries.

Behavioral performance on the challenge task. Group differences in cortical activation could be due to group differences in task performance. The two groups were therefore compared on true positives, false positives, true negatives, false negatives, total hits, total misses, d prime, and beta based on the challenge task data. Means, SDs, and results of one-way ANOVAs are presented in Table III. The only significant group difference was for d prime, with the Abuse only group having significantly poorer performance than the other three groups ($P < .02$, d = 1.11). To assess whether this factor could account for the Violence × Abuse × Hemisphere interaction, d prime was entered as a covariate and the MANOVA repeated. The three-way interaction remained significant, $F(1,17) = 6.6$, $P < .02$., as did the Abuse × Lobe × Hemisphere interaction, $F(2,16) = 3.5$, $P < .05$.

TABLE III. Means (SDs) and Between-Group *t*-Test Comparisons on Behavioral Performance on the Working Memory Challenge Task

	Controls (n = 9)	Abused (n = 4)	Violent (n = 5)	Abused violent (n = 5)	F	*P*
True positives	25.9 (7.3)	16.0 (12.7)	26.2 (7.1)	29.8 (6.9)	1.6	.23
True negatives	220.9 (10.1)	220.0 (2.8)	222.8 (6.7)	225.0 (0.7)	0.3	.78
False positives	5.1 (2.8)	6.0 (2.5)	2.2 (0.7)	1.0 (6.8)	0.5	.68
False negatives	10.1 (7.3)	20.0 (12.7)	10.8 (7.1)	6.2 (6.9)	1.6	.23
Total correct	246.7 (16.1)	236.0 (9.9)	248.0 (7.2)	254.8 (6.7)	1.2	.34
Total errors	15.2 (16.1)	26.0 (9.9)	12.0 (6.4)	7.2 (6.7)	1.2	.32
d prime	3.46 (1.33)	1.55 (0.65)	3.50 (0.89)	4.21 (0.38)	4.4	.01
Beta	341.3 (405.8)	4.7 (1.3)	317.3 (449.8)	335.2 (394.4)	0.6	.64

Control for IQ. Although groups did not differ significantly on demographic and cognitive factors, the Abuse Only group tended to have lower IQ scores than the other groups, and it is possible that this could contribute to the brain deficits observed in this group. To test this possibility, IQ was entered as a covariate and the MANOVA was rerun. The three-way interaction remained significant, $F(1,18) = 8.8$, $P < .008$, as did the Abuse × Lobe × Hemisphere interaction, $F(2,17) = 4.2$, $P < .04$.

Post-task recognition of objects. As a further measure of differential task engagement of the participant groups, groups were compared on their ability to recognize stimuli after the activation task was completed. Means, SDs, and results of one-way ANOVAs for three performance measures (true repeats, true single presentations, false positives) are presented in Table IV. There were no significant group differences ($P > .30$).

Task strategy. Group differences in cortical activation may be a function of differences in the strategy used to perform the task. Groups were compared on the extent to which they named the objects to themselves during presentation and the degree to which they rehearsed the items during the block. Means, SDs, and results of one-way ANOVAs are given in Table IV. There were no significant group differences on either task strategy ($P > .54$).

Mental activity during the control task. Although subjects were instructed only to fixate the dot on the blank screen, it is possible that group differences in cortical activation could be a

TABLE IV. Means (SDs) and Results of One-Way ANOVAs on Task Strategy, Mental Activity During Control Task, and Posttask Recognition Memory

	Controls (n = 9)	Abused (n = 4)	Violent (n = 5)	Abused violent (n = 5)	F	*P*
Task strategy						
Naming objects	3.4 (1.1)	3.3 (0.6)	3.2 (0.8)	3.5 (1.7)	.05	.98
Verbal rehearsal	3.0 (1.5)	3.7 (1.2)	2.2 (1.3)	3.3 (1.4)	0.7	.54
Control task						
Daydream	2.3 (1.0)	2.0 (1.0)	2.6 (1.1)	3.8 (1.0)	2.2	.12
Visualize objects	1.4 (0.7)	2.3 (0.6)	2.0 (1.0)	1.5 (1.0)	1.2	.33
Naming object	1.1 (0.4)	3.3 (0.6)	1.6 (0.9)	1.0 (0.0)	13.7	.0001
Posttask recognition						
Correct repeats	4.0 (1.9)	2.7 (2.0)	4.4 (2.0)	4.8 (1.5)	.75	.53
Correct singles	10.3 (5.2)	7.0 (6.6)	8.6 (4.1)	12.5 (5.3)	.77	.52
False positives	9.2 (4.5)	14.3 (12.0)	12.6 (6.4)	15.8 (3.2)	1.3	.30

function of group differences in mental activity engaged in during the control task, which is then subtracted from the experimental condition. Means, SDs, and one-way ANOVAs for the extent to which subjects engaged in three different types of mental activity during the control task (visualization of the objects, subvocal naming of the objects, and daydreaming) are given in Table IV. Groups differed on naming the object ($P < .0001$), with the Abuse Only group engaging in more naming of the objects during the control task compared with the other three groups ($P < .0001$). To assess whether group differences in naming could account for the three-way interaction, this variable was entered as a covariate in the MANOVA. The Violence × Abuse × Hemisphere interaction remained significant, $F\ (1,17) = 22.3$, $P < .0001$, as did the Abuse × Hemisphere × Lobe interaction, $F\ (2,14) = 5.0$, $P < .03$.

DISCUSSION

The key finding from this study is that seriously violent individuals who have suffered severe physical abuse as children show reduced functioning of the right hemisphere (particularly the right temporal cortex) during performance of a visual/verbal working memory task. A second finding is that individuals with a history of severe abuse, irrespective of violence status, show reduced cortical activation to this working memory task, especially in the left hemisphere. A third, but less clear-cut, finding is that those who have been severely abused but do not go on to become violent show relatively good right hemisphere functioning (especially the right superior temporal gyrus) in the face of relatively poor left hemisphere functioning (especially the left superior temporal gyrus). Effect sizes were all high, ranging from 1.92 for reduced right hemisphere functioning in Violent Abused individuals to 1.50 for reduced activation in Abused individuals.

The Violent Abused group showed reduced activation of the right hemisphere, particularly the right temporal cortex. Evidence for reduced right hemisphere functioning is consistent with several studies showing right hemisphere deficits in violent offenders [Day and Wong 1996; Drake et al., 1988; Evans and Park, 1997; Hucker et al., 1988], with two of these studies also showing right hemisphere deficits localized to the right temporal cortex. Why should right hemisphere dysfunction predispose to violence? There are four possible explanations. First, lesion studies and experimental neuropsychological studies have demonstrated that the right hemisphere plays a specialist role in processing emotion [Hellige, 1993]. In particular, patients with right hemisphere lesions are less able to recognize negative facial emotions, including anger and fear [Adolphs et al., 1996; Borod et al., 1990], and are less able to recognize fear in prosodic information [Schmitt et al., 1997]. Inability to accurately process and recognize signals of negative affect (e.g., anger, fear) in a protagonist during a fractious social encounter could contribute to inappropriate responding and escalation into an aggressive response.

Second, reductions in right hemisphere activation (particularly the anterior regions) have been associated with deficits in the withdrawal system, a system involved in the withdrawal of an individual from aversive and dangerous situations [Davidson et al., 1990; Davidson, 1998]. Violent and antisocial individuals have been characterized as physiologically underaroused, pathological stimulation seekers who are more likely to approach and get involved in dangerous risky situations to increase arousal levels back to normal [Raine et al., 1990; Zuckerman, 1994], findings consistent with reduced right hemisphere functioning and reduced withdrawal. Third, violent, antisocial, and criminal individuals have been consistently found to show poor fear conditioning [Raine, 1993], and two recent PET studies in humans have shown that fear conditioning preferentially activates structures in the right cerebral hemisphere, particularly right frontotemporal regions [Furmark et al., 1997; Hugdahl, 1998]. Consequently, reduced right hemisphere activation would be consistent with the poor fear conditioning observed in violent offenders. Fourth, the right hemisphere (including Brodmann areas 24 and 32 and frontotemporal regions) is viewed as dominant for the processing of pain [Hari et al., 1997; Hsieh et al., 1996], a finding consistent with the fact that stably aggressive individuals show reduced pain thresholds [Seguin et al., 1996]. Furthermore, violent offenders show a lack of concern for the future negative consequences of their antisocial behavior, which in turn may make such individuals less likely to refrain from physical encounters that have painful consequences [Raine, 1993]. When taken together, these four factors (poor fear conditioning, reduced pain perception, deficit in the withdrawal system, and poorer recognition of anger and fear) may constitute a significant predisposition toward violence.

Although left hemisphere dysfunction theory would predict reduced left hemisphere activation, and although the Violent Abused group was not significantly lower than Comparisons, findings do not necessarily contradict this perspective. The Violent Abused group showed relatively lower left hemisphere functioning than Comparisons, with an effect size of 0.82, which would be classified by Cohen [1988] as large. Consequently, although findings more strongly support reduced right hemisphere activation in the Violent Abused group, left hemisphere dysfunction should not be ruled out. In this context, recent prospective longitudinal findings show that life course persistent offenders, while showing verbal (putative left hemisphere) IQ deficits at age 11 years, had preexisting spatial (putative right hemisphere) deficits at age 3 years in the absence of verbal IQ deficits at age 3 years [Raine et al., 1999], findings broadly consistent with the current findings of strong right hemisphere activation deficits in light of moderate left hemisphere activation deficits. It is conceivable that serious antisocial and violent behavior is in part a product of early (possibly congenital) right hemisphere dysfunction combined with a later more acquired left hemisphere dysfunction. Future developmental fMRI research is essential for a full test of this hypothesis.

The Abuse × Hemisphere × Lobe interaction suggested that abused individuals, irrespective of violence outcome, show evidence of reduced cortical activation, particularly in the left hemisphere. This finding is broadly consistent with results of research showing structural and functional deficits in severely abused individuals localized to the left hemisphere [Bremner et al., 1995, 1997; Ito et al., 1993; Raskin 1997; Stein et al., 1997]. The Abused Only group additionally showed reduced activation in the left superior temporal gyrus, and additionally evidenced a strong deficit in performance on the working memory challenge task as indicated by d prime. This latter finding is consistent with two studies that have shown working memory deficits in those with a history of abuse [Bremner et al., 1995; Raskin, 1997]. These findings suggest, but by no means prove, that severe physical abuse early in life may contribute to left temporal dysfunction. Two alternative hypotheses that must be considered are (1) parents with inherent poor functioning of the (linguistic) left hemisphere have poor communication skills and use excessive physical means to discipline their children, who in turn inherit left hemisphere dysfunction, and (2) left hemisphere dysfunction is a risk factor for child abuse.

Recent studies have argued that the left hemisphere structural deficits in those with a history of severe abuse may be caused by the psychological consequences of traumatic stress following from this abuse, which results in abnormally high levels of corticosteroids that are neurotoxic to pyramidal cells in certain structures in the mesial temporal cortex [Gurvits et al., 1996; Ito et al., 1993]. An alternative hypothesis is that physical abuse leads to direct physical trauma to the head, which then results in brain dysfunction. We made a partial test of this counterhypothesis by assessing whether a history of head injury is overrepresented in abused individuals. Results showed that abused individuals (Abused Only and Violent Abused) were, if anything, slightly less likely to have a history of head injury (40%) compared with Comparisons (56%). These null findings are consistent with the hypothesis that the stress response to trauma contributes to brain dysfunction in abused individuals but do not rule out the possibilities that (1) there are physical sources of brain injury other than head injury that result in brain dysfunction in abused individuals and (2) very early brain dysfunction may be a predisposition toward (rather than a consequence of) childhood abuse.

While showing a relative reduction in left hemisphere functioning, the Abuse Only group showed surprisingly good right hemisphere functioning, in particular showing significantly *increased* activation in the right superior temporal gyrus compared with other groups, a brain area shown to be activated by some working memory tasks [McCarthy et al., 1994]. A critical but unaddressed question in violence and abuse research concerns why some, but not all, physically abused children become violent. The current findings suggest one provisional explanation. Abused individuals who go on to perpetrate serious violence have right hemisphere dysfunction that predisposes to violence via poor fear conditioning, reduced pain perception, faulty processing of emotions, and a deficit in the withdrawal system. In contrast, abused individuals who refrain from violence, although having left hemisphere dysfunction and impaired verbal working memory, have particularly good right temporal functioning, which may facilitate fear conditioning, processing of emotions, the withdrawal system, and pain perception. It is possible therefore that relatively good right hemisphere functioning protects individuals predisposed to violence (by virtue of being abused) from manifesting serious violence in adulthood.

Two apparent inconsistencies with the previous literature require clarification. First, the Violent Only group showed no significant brain deficits compared with Comparisons, in absolute terms having somewhat lower left hemisphere functioning than Controls ($d = 0.47$) but slightly higher right hemisphere functioning ($d = 0.29$). Although the previous literature predicts brain dysfunction in violence per se, these studies have been based on failed, caught offenders and have not tested the moderating effect of abuse on violence-biology relationships. The current results consequently raise the possibility that findings of this literature do not apply to nonabused violent offenders in the community and may be limited in their generalizability. Second, our previous PET study of murderers showed that murderers lacking psychosocial deficits were particularly characterized by prefrontal dysfunction. In this and other research [Raine et al., 1994, 1997, 1998], we cautioned against generalization of findings from selected, institutionalized groups of offenders. By the same token, we caution here about generalization of findings from community offenders to institutionalized or forensic populations. Clearly, as outlined by Volkow et al. [1995], differences in the exact nature of subject populations may have a considerable influence on the pattern of findings observed.

Five caveats on these findings must also be made clear. First, in interpreting findings, the assumption has been made that reduced activation is indicative of brain dysfunction in abused violent offenders. This may or may not be the case, and an alternative hypothesis is that reduced activation indicates more proficient, not deficient, brain functioning. We believe that this counterexplanation is implausible in this case for two reasons. First, the vast majority of studies on cognitive functioning in violent offenders find them to be impaired, not superior, compared with controls. Second, a proficiency explanation would predict that Violent Abused offenders would show significantly better performance with respect to IQ and behavioral performance on the working memory task, yet this was not the case. For these reasons we believe that reduced activation indicates poorer, not better, brain functioning in the Violent Abused group. The second caveat is that not all of the brain could be imaged in this study due to restrictions on scan time. Specifically, the regions most activated by the working memory task were Brodmann areas 10, 44, 45, 46, and 47 (frontal); 21 and 22 (temporal); and 18 and 19 (occipital). In consequence, statements and conclusions on localization of group differences to hemisphere or lobe must be placed in the context of the limited number of Brodmann regions activated and furthermore should not be construed as referring to brain areas not contained in these three slices, such as the parietal cortex. Third, because only a relatively small portion of the brain was imaged, broad conclusions about brain dysfunction in violent offenders cannot be drawn. Fourth, while we have recently found an 11% reduction in gray matter within the prefrontal cortex in those with Antisocial Personality Disorder [Raine et al., 2000], we did not find selective functional deficits in the prefrontal cortex in this study and instead found a tendency for stronger temporal lobe deficits. This may be due to the fact that temporal, rather than frontal, deficits may be of special relevance to violent behavior in particular rather than antisocial behavior in general. Fifth, sample sizes are small and results should be treated with caution. Nevertheless, despite these caveats, it is believed that this first fMRI study in violent offenders provides a basis on which future, more extensive, imaging work may build.

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