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ORIGINAL RESEARCH

Aberrant brain gray matter in murderers

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Abstract

Homicide is a significant societal problem with economic costs in the billions of dollars annually and incalculable emotional impact on victims and society. Despite this high burden, we know very little about the neuroscience of individuals who commit homicide. Here we examine brain gray matter differences in incarcerated adult males who have committed homicide ($n = 203$) compared to other non-homicide offenders ($n = 605$; total $n = 808$). Homicide offenders' show reduced gray matter in brain areas critical for behavioral control and social cognition compared with subsets of other violent and non-violent offenders. This demonstrates, for the first time, that unique brain abnormalities may distinguish offenders who kill from other serious violent offenders and non-violent antisocial individuals.

Keywords Brain imaging · Homicide · Voxel-based morphometry · Violence · Antisocial behavior

Introduction

Interpersonal violence is a significant societal problem, and homicide, in particular, stands out among violent acts for its severe and absolute consequences. More than 17,000 people are murdered each year in the United States (U.S. Department of Justice: Federal Bureau of Investigation, 2016) and estimates suggest the average cost per murder surpasses $17 million, including costs to victims, court proceedings, law enforcement, and loss of productivity. This sums to a staggering $255 billion dollar economic burden annually in the United States alone (DeLisi et al. 2010). These estimates, of course, cannot account for social and emotional consequences cast around the victims, relatives, and the rest of society. The gravity and prevalence of these costs, combined with increasing understanding of the complex bio-psycho-social influences on behavior, has fostered a perspective of viewing violence and homicide as a major public health concern, and has thus motivated the examination of individual differences that promote and protect individuals from these outcomes (Reidy et al. 2015).

Despite longstanding scientific interest, and its great impact on society, we still have limited knowledge of the neuroscience related to homicidal behavior. Examining the biological underpinnings of violence and homicide has become an increasingly tractable challenge encouraged by advancing technology in neuroscience, genetics, and related sciences. Modern brain imaging methods have provided a foundation for understanding pathophysiology and developmental factors that may contribute to violent behavior. A large and growing body of research highlights the roles of frontal, temporal, limbic, and paralimbic brain circuits for promoting and regulating aggression, antisocial behavior, and disinhibited behavior more generally. This work has provided some insight into the deficits exhibited by individuals with a propensity for even the most extreme violence (Bannon et al. 2015; Rosell and Siever 2015; Smith et al. 2016).

Some of the earliest functional neuroimaging studies that examined homicide offenders concluded that murderers were characterized by reduced activity in brain areas including

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lateral and medial prefrontal cortex (Raine et al. 1997; Raine et al. 1994; Raine et al. 1998), as well as medial temporal regions, including the amygdala, and extended temporal and parietal regions (Raine et al. 1997; Raine et al. 1998). These early studies relied on murderers who had been found *not guilty by reason of insanity* (NGRI), and thus include effects of comorbid psychosis and organic brain injury alongside those effects specifically related to homicidal behavior. In the same vein, more recent work still commonly comingles homicidal behavior with other psychiatric conditions, e.g., schizophrenia, or with violent antisocial behavior more generally, e.g. (Amen et al. 2007; Lam et al. 2017; Puri et al. 2008; Raine et al. 2000; Yang et al. 2010). These studies still highlight the role of frontal and temporo-limbic brain areas, but they are not sufficient to discriminate homicide from other violent outcomes or from other psychiatric disorders per se. Further, the degree to which these same brain structures may be useful in distinguishing between homicidal behavior and less severe forms of violence or antisocial behavior is less certain, as control groups are ordinarily comprised of non-incarcerated subjects. One recent study from our team reported that incarcerated adolescent boys who had committed homicide showed reduced gray matter in medial and lateral anterior temporal lobe and insula, relative to other serious offenders (Cope et al. 2014). Still, no prior study, to our knowledge, has compared the brains of adult homicide offenders directly with other violent offenders who have not committed a homicide. We hypothesize that homicide offenders will have deficits in areas of executive functioning and limbic control areas within the prefrontal cortex and anterior temporal cortex compared to non-homicide offenders.

Materials and methods

Experimental design

Here we sought to examine differences in brain structure between adult male inmates who have committed a homicide offense and those who did not. We used archival data from prior NIH-supported studies (see Acknowledgments) that included structural MRI data and pertinent assessment data. Participants were separated into one of three groups: homicide offenders, violent offenders who have not committed a homicide, and non-violent/minimally violent offenders. Voxel based morphometric (VBM) analyses were conducted to compare brain differences between groups.

Participants

We included incarcerated adult male participants from New Mexico and Wisconsin prisons who had undergone a structural MRI scan in one of our research studies using a 12 channel T1-weighted multi-echo sequence. The total sample included 998 incarcerated adult males with T1 (MPRAGE) scans. A number of participants were excluded due to abnormal radiology reports $n = 10$; Traumatic brain injury with loss of consciousness greater than 2 h $n = 43$; $n = 5$ were excluded due to their crime being too ambiguous to classify, $n = 50$ were excluded to the diagnosis of a psychotic disorder and $n = 82$ participants were excluded due to the inability to estimate the amount of time they had been incarcerated (a covariate in our models), thus, a total $n = 190$ participants were excluded from this omnibus sample. The final study sample included brain data from $n = 808$ incarcerated male adults.

Participants were categorized into three groups; Homicide, Violent non-homicide, and Non-violent/minimally violent. The "Homicide group" ($n = 203$) included men who were convicted of a homicide offense ($n = 81$); self-reported committing a homicide offense ($n = 72$); indicated during confidential research interviews a serious attempt to commit a homicide ($n = 32$) but failed or outcome was unknown; or were convicted of committing an attempted murder offense ($n = 18$). A report of a "serious attempt of homicide" included an explicit admission of attempting to commit a homicide offense during a confidential interview. Some participants were charged with a homicide offense under felony murder statutes (i.e., NM Stat § 30–2-1 (1996 through 1st Sess 50th Legis). These statutes refer to accomplices or co-conspirators of a dangerous crime i.e., armed robbery, home invasion, drug dealers, getaway drivers, etc., who are charged with murder even though they were not the ones who committed the actual homicide. These participants were not included in the Homicide category. Also, homicide offenders who's criminal file information indicated there was a strong possibility of the crime actually being an accidental death or that they were not directly involved in the homicide offense were excluded from the 'Homicide group'. These measures were taken to try and ensure all members of the 'Homicide group' were the perpetrators of a confirmed homicide/attempted homicide.

The "Violent Non-Homicide group" ($n = 475$) included individuals who had charges such as aggravated battery/robbery/assault, any crimes involving serious physical contact with a victim, armed robbery, domestic violence that included a weapon or great bodily harm, and kidnapping/unlawful confinement, arson (if there was a victim who endured physical harm), and reckless injury with weapons enhancement. Any criminal conviction with the enhancement of a deadly weapon or great bodily harm where there was physical contact between the participant and a victim (not an accidental or reckless car accident) were included. Participants who self-reported committing a violent crime such as; armed robbery; aggravated assault/battery, rape/sexual assault (child or adult) were categorized as violent. In the event that the participant had a charge of a violent offense but through further investigation through their file revealed that they did not have

physical contact with a victim or intentional contact with the victim (ex. Aggravated battery due to a reckless driving incident or armed robbery due to theft of a weapon during a robbery in which they did not come into contact with the victims) with the absence of other violent charges and no self-reported violent crimes, they were considered minimally violent.

"Minimally Violent Group" (n = 130) included those inmates with charges for, or self-reporting less than 3 simple assault/battery/domestics (no weapon enhancements or serious injury), driving while under the influence (DUI/DWI), drug possession or trafficking, prostitution, weapons possession or trafficking, arson of an uninhabited dwelling or property (with no victim), child abuse/neglect (unless intentional physical harm came to the child), reckless driving, voyeurism, possession of child pornography, pimping/trafficking, unlawful confinement/kidnapping (if there was no physical contact with a victim), resisting arrest, battery upon a peace officer, theft, forgery, burglary, fraud, driving offenses, escape, failure to appear, vandalism, and property damage. In the event that a participant was convicted of a violent crime, but according to their criminal file did not have physical contact with a victim they were included as minimally violent. Offenders who committed vehicular homicide while under the influence or due to reckless driving such as speeding, or running a stop sign, or participants who were charged with felony homicide but did not actually commit the index offense, who also did not have any other violent convictions or self-reports, were included in this group. Participants, who did not self-report committing any violent crimes (as defined in the Violent Non-homicide group description) and did not have any criminal charges for a violent offense, were also considered non-violent/minimally-violent.

All information for New Mexico participants were gathered using information from participant's official criminal files from which we used arrest data, incarceration history such as movement data, parole data, conviction history, disciplinary reports, good time reports, police reports, victim impact statements, participant statements and letters, as well as public court records and self-reported criminal history during confidential interviews. For Wisconsin participants we used court records as well as public institutional information from the Wisconsin correctional department's inmate lookup website which provided information about incarceration history through their movement records and convictions history. For all participants we also used public newspapers and court documents such as appeals to corroborate institutional information and gain more information about the circumstances of a crime such as if others were involved, possible motivations for the crime or any other relevant history or circumstances. Participant interviews such as for scoring psychopathy were used as well to determine level of violence or to gain more insight into the circumstances surrounding any crimes committed.

Participants were excluded for abnormal radiology reports, e.g. having white matter lesions, large cysts, etc. Participants were also excluded if their crime was too ambiguous to adequately categorize. The present study reports from a final sample of n = 808 incarcerated adult male offenders. This research was approved by multiple IRBs, including the Ethical and Independent Review Services (E&I), the University of Wisconsin-Madison, divisions of the Corrections Department of Wisconsin and The New Mexico Corrections Department as well as the Office of Human Research Protections (OHRP). All individuals volunteered to participate after providing written informed consent. Participation did not affect institutional status (e.g., security level, privileges, and parole or release date) and participants were paid for their time at a rate commensurate with pay for work assignments at their facility.

Assessments

Psychopathy

All offenders were assessed for psychopathy using the Psychopathy Checklist-Revised (PCL-R; (Hare 2003). The PCL-R is an expert-rated semi-structured interview that assesses the presence of 20 traits and behavioral patterns that may be evident across the lifespan (e.g., shallow affect, callousness, lack of guilt or remorse, juvenile delinquency, poor behavioral controls, and impulsive/antisocial behaviors). These 20 items are scored on a three-point scale (0, 1, and 2) indicating no-evidence, some evidence, and pervasive evidence. Scores range from 0 to 40 and the accepted diagnostic cutoff for psychopathy is 30 and above; however, these scores are also commonly used on a continuous scale (Hare and Neumann 2005) and PCL-R total scores were used for all analysis.

Substance use severity

Substance use severity was quantified as the total months of substance use derived from a modified survey based on the Addiction Severity Index (McLellan et al. 1992), ASI-X. Scores were divided by age (at the time of MRI scan) to account for opportunity for use, and square root transformed to correct for skew.

Intelligence

IQ estimates were calculated using the vocabulary and matrix reasoning subtests of the *Wechsler Adult Intelligence Scale III* (WAIS-III) (Wechsler 1997), a stable estimate of IQ (Ryan et al. 1999).

Psychiatric disorders

From the Structured Clinical Interview for DSM –IV Axis I and II Disorders (SCID-I; SCID-II) (First et al. 2002) offenders were assessed for mood, anxiety, psychotic and personality disorders. Offenders with a history of psychosis or psychotic disorders were excluded from the analyses.

Other assessments

Trained researchers administered a post-head injury symptoms questionnaire to evaluate history of traumatic brain injury (TBI) (King et al. 1995). Participants were excluded if they had a traumatic brain injury resulting in loss of consciousness for longer than two hours or had MRI findings indicative of brain injury by radiological review.

Time in prison

Time spent in prison estimates were gathered using participant's movement record or self-reported data from their institutional records and PCL-R interviews. Time in prison was divided by age and square root transformed to address skewness (see Table 1).

MRI acquisition

High-resolution T1-weighted structural MRI scans were acquired on the Mind Research Network Siemens 1.5 T Avanto mobile scanner, stationed at one of the eight prisons in this study, using a multi-echo MPRAGE pulse sequence kindly provided by Massachusetts General Hospital Radiology Department (repetition time = 2530 ms, echo times = 1.64 ms, 3.50 ms, 5.36 ms, 7.22 ms, inversion time = 1100 ms, flip angle = 7°, slice thickness = 1.3 mm, matrix size = 256 × 256) yielding 128 sagittal slices with an in-plane resolution of 1.0 mm × 1.0 mm. Data were pre-processed and analyzed using Statistical Parametric Mapping software (SPM12; Wellcome Department of Cognitive Neurology, London, UK; http://www.fil.ion.ucl.ac.uk/spm). T1 images were manually inspected by an operator blind to subject identity and realigned to ensure proper spatial normalization.

Images were spatially normalized to the SPM12 T1 Montreal Neurological Institute (MNI) template using non-linear registration, segmented into gray matter, white matter, and cerebrospinal fluid, and modulated with the Jacobian determinants to preserve total volume (Ashburner and Friston 2000). Finally, the images were resampled to 1.5 × 1.5 × 1.5 mm and smoothed with a 10 mm full-width at half-maximum (FWHM) Gaussian kernel. Voxels with a gray matter value of < .15 were

Table 1 Comparison of covariates across groups of incarcerated offenders

Variables.	Subject groups			Group differences
	Homicide (A)	Violent non-homicide (B)	Minimally violent non-homicide (C)	
n	203	475	130	
Age	33.13 (8.5)	34.13 (9.2)	33 (8)	$F = 1.573$ $p = .208$
IQ	96.4 (13.6)	98 (13.4)	99.3 (13.2)	$F = 2.118$ $p = .121$
PCL-R Total Score	23.4 (6.7)	21.8 (6.9)	20.7 (7.7)	$F = 6.596$ $p = .001$ A > C $t(350) = -3.422$ $p = .001$ A > B $t(751) = -2.804$ $p = .005$
Substance Use	7.1 (5.6)	7.4 (6.8)	9.24 (7.6)	$F = 4.844$ $p = .008$ C > A $t(350) = 3.003$ $p = .003$ C > B $t(671) = 2.694$ $p = .007$
Total Brain Volume (GM + WM)	1191.631 (103.966)	1190.490 (106.129)	1213.922 (109.873)	$F = 2.730$ $p = .066$
Time in prison (Months/Age)	2.8 (1.7)	2.2 (1.6)	1.4 (1.3)	$F = 27.960$ $p = .000$ B > C $t(603) = -5.011$ $p = .000$ A > C $t(332) = -7.556$ $p = .000$ A > B $t(675) = -4.128$ $p = .000$

Significant group differences indicated by ANOVA are followed up by t-test comparisons between groups. Substance Use is quantified as a severity measure based on how many months the individual engaged in regular (3+ times/week) substance use, divided by age to account for opportunity for use. Total brain volume is a combination of total gray matter + white matter. Time in prison is calculated as approximate months in prison and divided by age

excluded in order to remove possible edge effects between gray matter and white matter.

Whole brain analysis

One way ANOVA was performed on a voxel-by-voxel basis over the whole brain using SPM12 to evaluate differences in regional gray matter volumes between Homicide ($n = 203$), Violent Non-Homicide ($n = 475$) and Minimally Violent ($n = 130$) offenders, with all three groups included as factors in each analysis. The ANOVA model included each subject's total brain volume (i.e., gray matter plus white matter), PCL-R total scores, substance use severity, age at time of scan, IQ, and time in prison variables as covariates. Whole brain analyses using the False Discovery Rate for control over Type I error, were performed for all comparisons. Results from comparisons between homicide offenders and violent non-homicide offenders are presented in Figs. 1, 3 and Table 2. Results from comparisons between homicide offenders and all non-homicide offenders are presented in Fig. 2.

Results

Homicide offenders ($n = 203$) showed robust deficits in ventromedial/orbitofrontal cortex, anterior temporal cortex, ventrolateral and dorsolateral prefrontal cortex, dorsomedial prefrontal cortex, insula, cerebellum, dorsal anterior cingulate, mid-cingulate, and posterior cingulate cortex extending into the precuneus and superior parietal regions compared to all offenders who have not committed a homicide offense ($n = 605$) (see Fig. 2). These results remained stable when comparing the homicide group against other severely violent offenders ($n = 475$) (see Figs. 1, 3; Table 2). Effects here were not attributable to age, IQ, psychopathy, substance use severity, or time in prison, which were entered as covariates in all analyses along with total gray and white matter to control for global differences in brain size (see Table 1). Comparisons between the violent (no-homicide) and minimally-violent offenders yielded mostly null results, and no results survived correction for multiple comparisons.

Supplemental analysis

Following recommendations from review, and due to potential interest in alternative categorization strategies, we examined gray matter differences between additional subcategories of our primary groups. These analyses compared convicted homicide offenders versus self-report homicide offenders and attempted homicide offenders vs. completed homicide

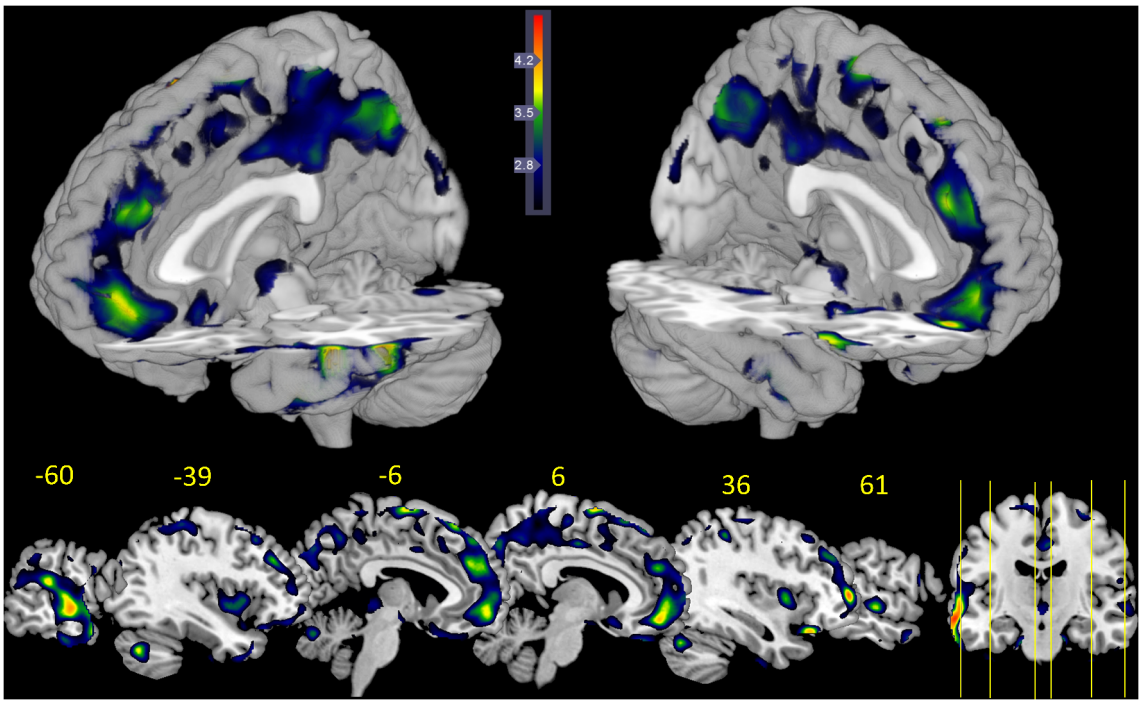


Fig. 1 Violent, Non-Homicide Offenders ($n = 475$) versus Homicide Offenders ($n = 203$). Areas where homicide offenders exhibit reduced gray matter density compared to other violent offenders are highlighted in blue/green. The color scale represents *t*-values for the comparison at each voxel in the brain with a $p < .05$ threshold corrected for the expected false-discovery rate across the whole brain. A selection of anatomical labels and corresponding statistical values and coordinates are given in Table 1

Table 2 Coordinates and Labels for selected Violent Non-Homicide versus Homicide group effects

Cluster size K.	*t vlaue*	FDR *p* value	x	y	z	L/R	Lobe	Label	Brodmann Area
1155	4.51	0.032	−66	−13	−14	L	Temporal Lobe	Inferior Temporal Gyrus	BA 21
	4	0.032	−57	3	−21	L	Temporal Lobe	Middle Temporal Gyrus	BA 21
	3.96	0.032	−63	−33	15	L	Temporal Lobe	Superior Temporal Gyrus	BA 22
283	4.31	0.032	18	18	63	R	Frontal Lobe	Superior Frontal Gyrus	BA 6
	3.98	0.032	27	3	63	R	Frontal Lobe	Superior Frontal Gyrus	BA 6
462	4.24	0.032	46	26	−17	R	Frontal Lobe	Inferior Frontal Gyrus	BA 47
	3.89	0.032	52	32	−9	R	Frontal Lobe	Inferior Frontal Gyrus	BA 47
	3.41	0.032	48	42	−9	R	Frontal Lobe	Inferior Frontal Gyrus	BA 47
234	4.23	0.032	37	54	4	R	Frontal Lobe	Middle Frontal Gyrus	BA 10
	3.38	0.032	48	45	3	R	Frontal Lobe	Inferior Frontal Gyrus	BA 46
235	4.16	0.032	−52	20	28	L	Frontal Lobe	Middle Frontal Gyrus	BA 9
	3.67	0.032	−56	27	7	L	Frontal Lobe	Inferior Frontal Gyrus	BA 45
	3.53	0.032	−56	18	16	L	Frontal Lobe	Inferior Frontal Gyrus	BA 44
	4.04	0.032	6	48	−12	R	Frontal Lobe	Medial Frontal Gyrus	BA 11
708	3.76	0.032	−6	56	−9	L	Frontal Lobe	Superior Frontal Gyrus	BA 10
125	3.97	0.032	−28	15	−36	L	Temporal Lobe	Superior Temporal Gyrus	BA 38
101	3.95	0.032	−12	−79	40	L	Parietal Lobe	Precuneus	BA 19
86	3.84	0.032	−12	−73	−23	L	Cerebellum	Uvula	*
408	3.82	0.032	−3	41	28	L	Frontal Lobe	Medial Frontal Gyrus	BA 9
	3.65	0.032	−4	51	28	L	Frontal Lobe	Superior Frontal Gyrus	BA 9
	3.64	0.032	6	47	25	R	Frontal Lobe	Medial Frontal Gyrus	BA 9
79	3.8	0.032	58	−21	−3	R	Temporal Lobe	Middle Temporal Gyrus	BA 21
26	3.77	0.032	−24	−63	57	L	Parietal Lobe	Superior Parietal Lobule	BA 7
116	3.76	0.032	−36	35	30	L	Frontal Lobe	Middle Frontal Gyrus	BA 9
	3.49	0.032	−30	45	24	L	Frontal Lobe	Superior Frontal Gyrus	BA 9
78	3.75	0.032	−40	−66	−36	L	Cerebellum	Inferior Semi-Lunar Lobule	*
80	3.69	0.032	46	−60	−21	R	Cerebellum	Tuber	*
82	3.68	0.032	−12	42	48	L	Frontal Lobe	Superior Frontal Gyrus	BA 8
58	3.66	0.032	37	8	3	R	Sub-lobar	Insula	BA 13
92	3.65	0.032	38	−70	−30	R	Cerebellum	Inferior Semi-Lunar Lobule	*
35	3.55	0.032	60	15	18	R	Frontal Lobe	Inferior Frontal Gyrus	BA 45
34	3.54	0.032	33	42	34	R	Frontal Lobe	Middle Frontal Gyrus	BA 8
135	3.54	0.032	2	−69	45	R	Parietal Lobe	Precuneus	BA 7
14	3.53	0.032	−9	−94	19	L	Occipital Lobe	Middle Occipital Gyrus	BA 18
16	3.52	0.032	−54	0	40	L	Frontal Lobe	Precentral Gyrus	BA 6
41	3.51	0.032	42	33	28	R	Frontal Lobe	Middle Frontal Gyrus	BA 9
58	3.48	0.032	−52	33	−9	L	Frontal Lobe	Inferior Frontal Gyrus	BA 47
40	3.46	0.032	−32	26	46	L	Frontal Lobe	Superior Frontal Gyrus	BA 8
10	3.44	0.032	9	36	55	R	Frontal Lobe	Superior Frontal Gyrus	BA 6
10	3.44	0.032	4	−10	42	R	Frontal Lobe	Paracentral Lobule	BA 31
61	3.44	0.032	3	−58	49	R	Parietal Lobe	Precuneus	BA 7
19	3.43	0.032	−8	62	6	L	Frontal Lobe	Medial Frontal Gyrus	BA 10
15	3.41	0.032	0	−36	67	L	Parietal Lobe	Postcentral Gyrus	BA 5
9	3.4	0.032	37	−37	49	R	Parietal Lobe	Inferior Parietal Lobule	BA 40
8	3.39	0.032	16	9	−14	R	Frontal Lobe	Inferior Frontal Gyrus	BA 47
9	3.38	0.032	−24	60	1	L	Frontal Lobe	Middle Frontal Gyrus	BA 10
10	3.36	0.032	−44	−39	55	L	Parietal Lobe	Inferior Parietal Lobule	BA 40

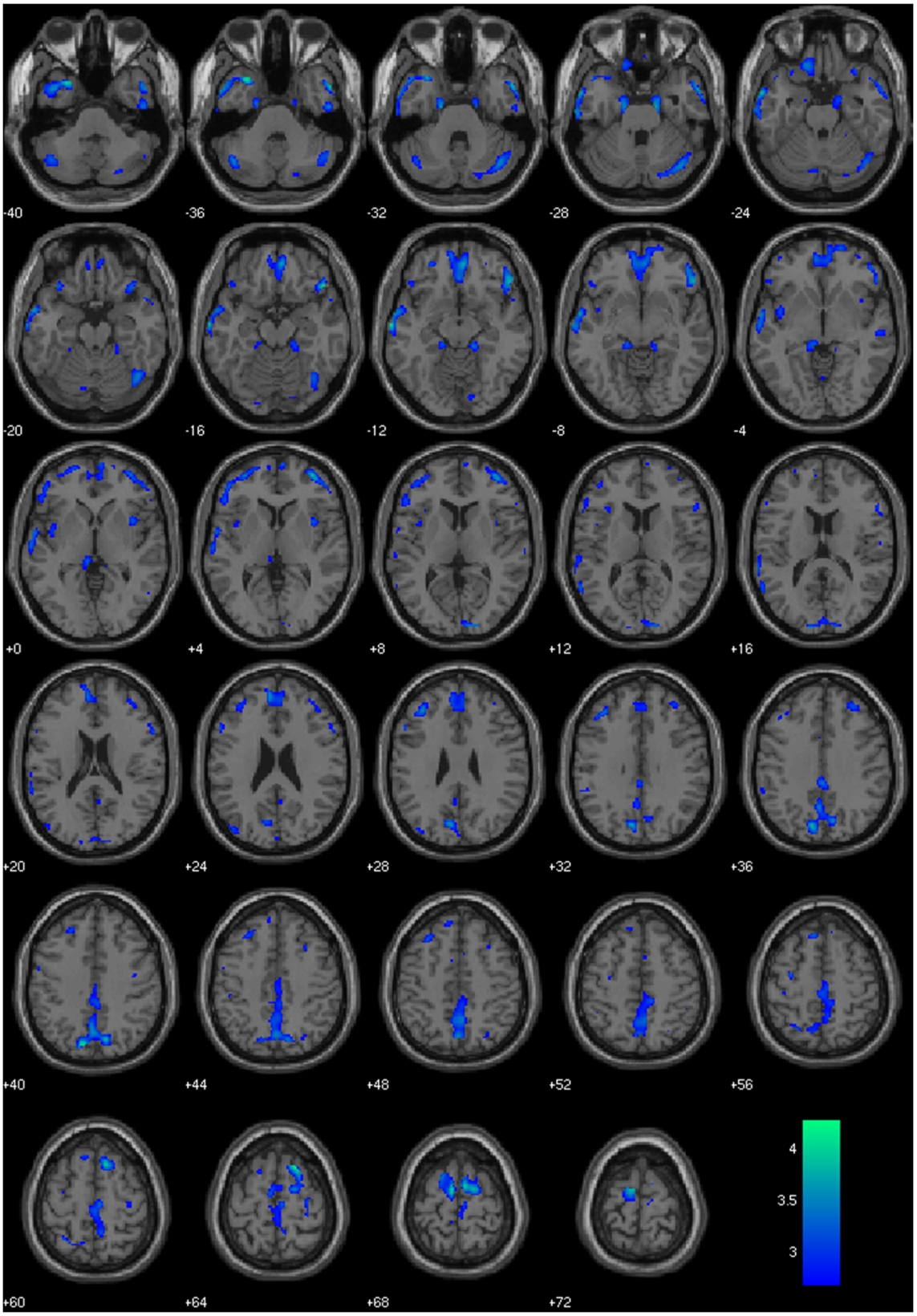
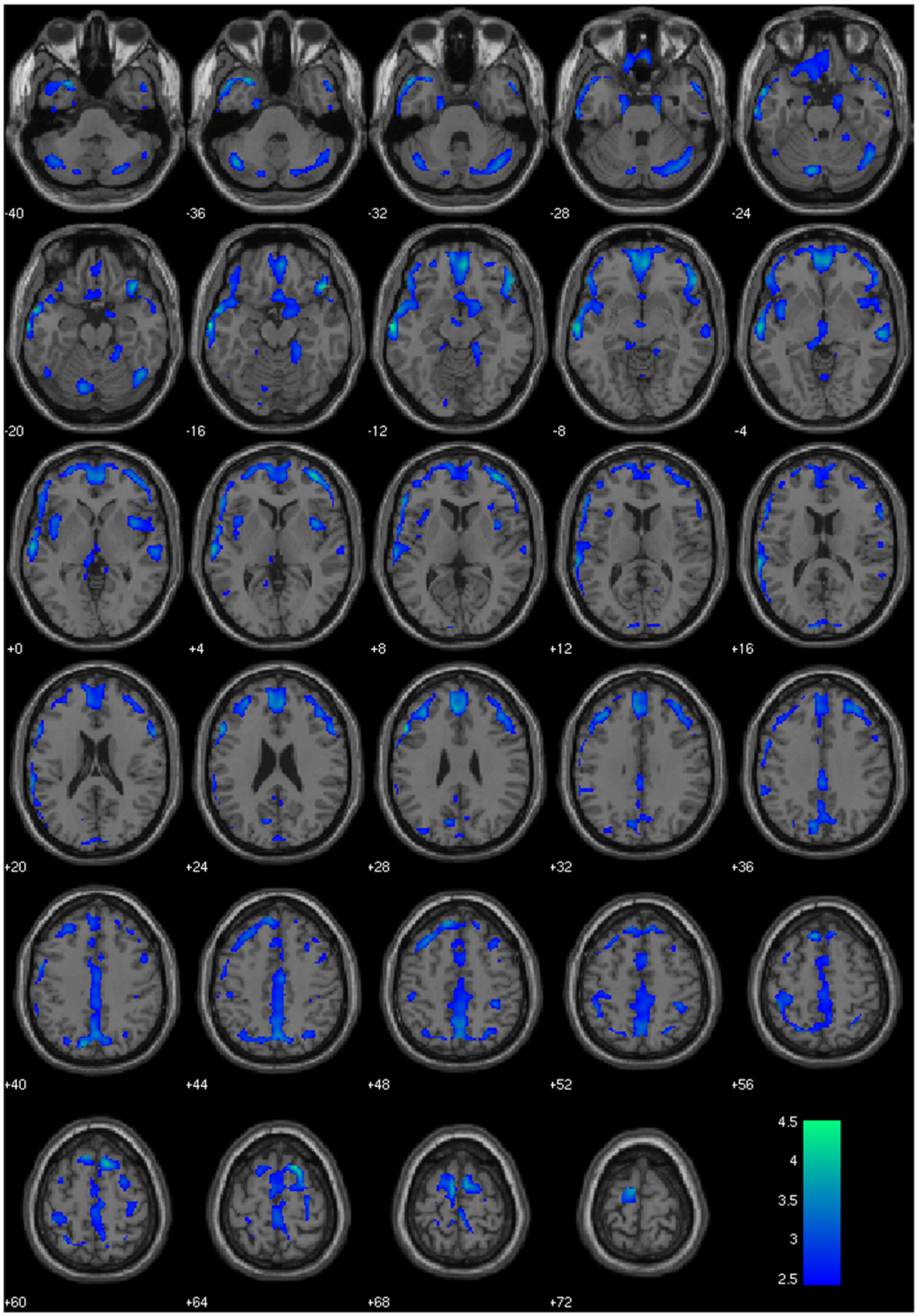


Fig. 2 All Non-Homicide Offenders ($n = 605$) versus Homicide Offenders ($n = 203$). Areas where homicide offenders exhibit reduced gray matter density compared to non-homicide offenders are highlighted in blue/green. The color scale represents *t*-values for the comparison at each voxel in the brain with a $p < .05$ threshold corrected for the expected false-discovery rate across the whole brain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◀ **Fig. 3 Violent, Non-Homicide Offenders (n = 475) versus. Homicide Offenders (n = 203).** This figure shows a single generic brain in axial slices. Areas where homicide offenders exhibit reduced gray matter density compared to other violent offenders are highlighted in blue/green. The color scale represents t-values for the comparison at each voxel in the brain with a $p < .05$ threshold corrected for the expected false-discovery rate across the whole brain. A selection of anatomical labels and corresponding statistical values and coordinates are given in Table 1

offenders, including parsing self-reported attempted homicide and convicted attempted homicide. No significant differences in gray matter were found between these subgroups, in any regions highlighted in our primary analysis here. These supplementary analyses further justify our initial categorization strategy of considering these groups together as homicide offenders. These analyses are provided in more detail supplementary material (S1).

Discussion

This study examined gray matter differences among incarcerated male offenders comparing those who have committed a homicide and those who have not. We report widespread reductions in gray matter affecting brain regions involved in emotional processing, behavioral control, executive function, and social cognition. These results were stable when comparing against both subcategories of violent and minimally violent groups. Comparisons between the violent (non-homicide) and non-violent groups yielded mostly null results, suggesting that major individual differences distinguish those who committed homicide, and that the brains of ordinary violent offenders do not differ much, structurally, from minimally violent and antisocial inmates.

The reductions in gray matter among homicide offenders were evident in a number of brain areas important for affective processing, social cognition, and strategic behavioral control. Prominently featured in these results are the orbitofrontal/ventromedial prefrontal cortex, the anterior temporal cortex, insula, medial prefrontal/anterior cingulate and precuneus/posterior cingulate cortex. For example, the abilities to assess the cognitive perspective and emotional states of others is often described as theory of mind (ToM) and empathy, and these abilities are important for effective social-cognitive function and adaptive social behavior. Prior neuroimaging studies suggest important roles for the orbitofrontal cortex, medial prefrontal cortex, temporal poles, insula, and anterior cingulate cortex in tasks that require assessment of others' cognitive states and feelings (Decety 2011; Olson et al. 2007; Völlm et al. 2006). Partially overlapping with these circuits, brain networks involved in regulating one's own emotional states draw on ventromedial, ventrolateral, dorsomedial, and dorsolateral prefrontal cortex under varied conditions of appraisal and control (Hutcherson et al. 2012; Ochsner et al. 2012). The orbitofrontal cortex has been identified for its role in planning/executing behavior based on expected outcomes (Howard et al. 2015; Rich and Wallis 2016) experiencing regret over one's behavior (Camille et al. 2004; Coricelli et al. 2005), and effective moral decision-making (Moll et al. 2002). These frontal regions exert influence on primary emotional regions such as the amygdala, sensory areas, and parietal integration areas. Further, the anterior cingulate and insula have been described for their combined role in redistributing cognitive resources effectively during executive control and other forms of directed cognitive appraisal (Bush et al. 2000; Ochsner and Gross 2005; Ochsner et al. 2012). By considering first the roles of larger functional networks, it follows that limitations in some individual, specific brain regions may affect a number of varied functional properties of the brain affecting behavior.

Reduced gray matter in many of these same brain regions have been previously implicated in studies comparing violent and/or homicide offenders characterized with other neurological and psychiatric issues with healthy controls e.g. (Amen et al. 2007; Lam et al. 2017; Raine et al. 1997, 1998, 2000). The present findings also expand the network of brain areas previously identified in youth who had committed homicide – namely anterior-medial and lateral temporal lobes, and the insula (Cope et al. 2014). These findings also align with prior work that has related similar brain abnormalities with aggressive behavior (Rosell and Siever 2015), and more general impairments in behavioral control and decision-making; for instance, among those with persistent antisocial behavior (Raine et al. 2000) and youth with conduct disorder (Fairchild et al. 2011). Further, these regions overlap with many paralimbic regions related to psychopathic traits (Anderson and Kiehl 2012; Ermer et al. 2012; Ermer et al. 2013; Gregory et al. 2012). Psychopathic traits remain among the best predictors of future violence in released offenders (Hare et al. 2000; Salekin et al. 1996). Continuing research should therefore consider how brain imaging data may reveal the pathophysiological and developmental origins of psychopathic traits, and how these may combine with social and environmental factors to predict violent outcomes, particularly homicide.

In the context of this growing literature, it should be recognized that the localized deficits in gray matter exhibited in this sample of homicide offenders are not necessarily specific to homicidal behavior. Instead, these patterns may indicate impairment across a wide range of

emotion and cognitive systems that together reduce essential checks and balances in executive function, moral judgement, and behavioral controls. The evident discriminability of homicide offenders in this sample based on gray matter may therefore be one of degree, demonstrating reliable separation in line with the severity of these effects.

Limitations and future directions

Our study included a number of control measures for possible moderating variables, such as psychopathy, IQ, age, and time in prison. However, it is possible that homicide offenders differ from violent offenders in other constructs without psychometric coverage. For example, there may be dimensions of impulsivity that were not captured by our assessments that may differ between groups (i.e., homicide offenders may be more impulsive than non-homicide offenders, on average). We address a common limitation of research examining homicide that relies only on official conviction data. This introduces limitations of the criminal justice system, policing biases, and sentencing strategies (e.g. plea bargains) which add noise to models intended to hone in on specific offenses. By combing our best resources including official convictions, court-records, and by including self-reported incidents, we have intended to capture more precise groupings. Comparisons provided in supplementary materials reinforce the merits of this strategy, though it comes with its own limitations and likely remains imperfect.

In an attempt to limit variability attributable to external factors and gross neurological abnormalities, we have excluded individuals with major head injuries and significant radiological findings. While it is not our intention to limit all variability contributing to abnormal brain structure, this choice reflects a motivation to focus on individual differences not directly attributable to injury or other acute neurological events. We fully intend to focus future efforts on examining these relationships directly, as brain injuries represent a major influence on neurological function and behavior. We hope this initial work leads to more research in this area and more granular parcellation of constructs relevant to homicidal behavior in particular.

These results may also have important implications for the criminal justice system. Indeed, brain imaging data is increasingly being used in court (Farahany 2016; Gaudet and Marchant 2016). While this report demonstrates aggregate differences between homicide offenders and other violent offenders that are highly statistically significant, this should not be mistaken for the ability to identify individual homicide offenders using brain data alone, nor should this work be interpreted as predicting future homicidal behavior. This study does include a very large sample but we nevertheless recommend continued efforts for replication and extension. Additionally, as previous work comparing violent individuals to community samples have shown violent offenders have some enhanced brain regions compared to community controls (De Brito et al. 2009; Tiihonen et al. 2008), this current study does not include a comparison sample of community members. Given the heterogeneity and complexity of homicide behavior, contrasting an incarcerated individual to a member of the community may introduce additional confounding factors related to effects of socioeconomic status, incarceration, policing and sentencing and a multitude of other environmental and biological factors. The description of abnormal neural networks among homicide offenders is a key step in furthering our understanding of the connection between biology and serious violent behavior. As such, this work represents an incremental step in making our society safer by demonstrating the crucial role of brain health and development in the most extreme forms of violence represented among antisocial populations.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request. All processed data (completely de-identified), code, and materials used will be made available to any scientist seeking to replicate or re-analyze the data.

Compliance with ethical standards

Conflict of interest The authors report no competing interests.

Ethical approval This research was approved by multiple IRBs, including the Ethical and Independent Review Services (E&I), the University of Wisconsin-Madison, divisions of the Corrections Department of Wisconsin and The New Mexico Corrections Department as well as the Office of Human Research Protections (OHRP).

Informed consent All individuals volunteered to participate after providing written informed consent. Participation did not affect institutional status (e.g., security level, privileges, and parole or release date) and participants were paid for their time at a rate commensurate with pay for work assignments at their facility.

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