



Research paper

Adverse childhood experiences, exposure to the World Trade Center attacks, and chronic symptoms of depression, PTSD, and unhealthy drinking

Angela M. Parcesepe^{a,*}, Jenna Sanborn^b, Julia S. Sisti^c, Janna Metzler^c

^a University of North Carolina at Chapel Hill, Chapel Hill, NC, United States of America

^b Institute for Implementation Science in Population Health, City University of New York, New York, NY, United States of America

^c New York City Department of Health and Mental Hygiene, World Trade Center Health Registry, New York, NY, 11101, United States of America

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ABSTRACT

Background: Exposure to potentially traumatic events (PTE) is common and associated with poor mental health. Little is known about factors that influence the relationship between PTE and long-term mental health.

Methods: This sample included 26,178 individuals who were 18 years or older on September 11, 2001, enrolled in the World Trade Center Health Registry, and completed the Wave 5 survey in 2020–21. We investigated the extent to which adverse childhood events (ACE) modified the relationship between WTC-related PTE exposure and the risk of prevalent or persistent symptoms of post-traumatic stress disorder (PTSD), depression, and unhealthy drinking on multiplicative and additive scales. For each outcome, we fit a log-binomial regression model including categorical variables for WTC-related PTE and ACE, their interaction, and covariates. Adjusted risk ratios were estimated for each joint level of PTE and ACE, using the doubly unexposed group (medium/low PTE and no ACEs) as reference.

Results: ACE exposure and WTC-related PTE exposure were independently associated with greater risk of prevalent and persistent symptoms of PTSD, depression, and unhealthy drinking. There was evidence of positive additive and negative multiplicative modification by ACE exposure of the relationship between WTC-related PTE exposure and symptoms of persistent PTSD and depression.

Conclusion: Findings suggest that adverse experiences in childhood increase the risk and persistence of symptoms of PTSD and depression after mass trauma in adulthood. Screening of traumatic events throughout the life course may increase identification of individuals at increased risk of poor mental health outcomes following subsequent PTE exposure.

1. Introduction

Exposure to potentially traumatic events (PTE) is common throughout the United States (US) with approximately 80 % of the US population exposed to a potentially traumatic event in their lifetime (Benjet et al., 2016; Schein et al., 2021). PTE exposure in adulthood has been associated with increased risk of poor mental health and substance use, including increased risk of post-traumatic stress disorder (PTSD), depression, and unhealthy alcohol use (Forman-Hoffman et al., 2012; Sunderland et al., 2016). A systematic review found that among civilians in the US, the lifetime prevalence of PTSD ranged from 3 %–27 % (Schein et al., 2021). However, great variability exists in the acute and long-term mental health impact of PTE exposure. Among those exposed

to a traumatic event, it has been estimated that between 10 and 30 % of individuals will develop PTSD (Diamond et al., 2022; Shalev et al., 1998). The risk of PTSD varies by type of PTE exposure (Kessler et al., 2017; Santiago et al., 2013). Experiencing sexual violence and other interpersonal PTE types has been associated with increased likelihood of PTSD compared to non-interpersonal types of PTE (Overstreet et al., 2017; Wamser-Nanney et al., 2018). In addition, the prevalence of PTSD decreases with increasing time from PTE exposure (Diamond et al., 2022). Similarly, PTE exposure has been associated with increased risk of depression and unhealthy drinking with prevalence varying by type of PTE exposure and time since PTE exposure (Forman-Hoffman et al., 2012; Fullerton et al., 2004; Galovski et al., 2023; Hoppen et al., 2021; Steel et al., 2009). While on average, the mental health impact of PTE

* Corresponding author.

E-mail address: angela.parcesepe@unc.edu (A.M. Parcesepe).

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exposure decreases over time, a subpopulation of individuals experiences persistent mental health sequelae of PTE exposure up to decades later (Holbrook et al., 2002; Karchoud et al., 2024).

The 2001 attack on the World Trade Center (WTC) directly and indirectly affected thousands of residents, workers, and passersby. Mental health impacts of the WTC attacks have been widely documented for more than 20 years (Daniels et al., 2021; Hamwey et al., 2020; Lowe et al., 2023). Exposure to the WTC attacks has been associated with poor mental health, including symptoms of depression, anxiety, PTSD, and unhealthy drinking up to 15 years after the WTC attack (Daniels et al., 2021; Hamwey et al., 2020; Jordan et al., 2019; Lowe et al., 2023). Poor health-related quality of life and unmet need for mental health care have also been commonly reported among those impacted by the WTC attack (Jordan et al., 2019). Although most WTC survivors have not experienced persistent mental health symptoms, a minority have reported persistent mental health symptoms since the WTC attack (Lowe et al., 2023). Understanding factors that influence the relationship between WTC-related PTE and long-term mental health symptoms can identify subpopulations at greater risk of long-term mental health concerns following terror-related PTE exposure and inform strategies to screen and link individuals at increased risk for long-term mental health concerns to timely and effective evidence-based mental health care.

Understanding factors that influence the relationship between PTE exposure and persistent mental health symptoms remains limited. However, emerging research suggests that childhood adversity may influence the long-term mental health impact of subsequent PTE exposure in adulthood (Dunn et al., 2017; Molina and Whittaker, 2022). Adverse childhood experiences (ACE) are PTE that occur in childhood and include experiences such as violence, abuse, and neglect, among others (Forman-Hoffman et al., 2012). ACEs are commonly reported in the US. Most (61 %) adults in the US have experienced at least one ACE, and 16 % have experienced four or more (Hustedde, 2021). ACEs have been consistently associated with long-term mental health effects into adulthood, including increased risk of depression, PTSD, and unhealthy drinking (Bellis et al., 2019; Hughes et al., 2017; Hughes et al., 2021; Le et al., 2018; Watters et al., 2023). However, little remains known about the influence of childhood adversity on the long-term mental health impact of exposure to collective trauma or terrorism. A study of individuals exposed to the 2013 Boston Marathon Bombing found that prior PTE exposure was associated with more severe post-traumatic stress symptoms following the Boston Marathon Bombing (Garfin et al., 2020). In addition, a study of a U.S. national sample with no prior history of mental health disorders found that among those with direct exposure to the WTC attacks, childhood maltreatment increased the risk of internalizing symptomatology (related to symptoms of depression, anxiety, and PTSD) (Meyers et al., 2015). This study aims to investigate the extent to which ACE exposure modifies the relationship between subsequent WTC-related PTE exposure and prevalent or persistent symptoms of PTSD, depression, and unhealthy drinking.

2. Methods

2.1. Study population

Participants were enrollees in the World Trade Center Health Registry (WTCHR), a longitudinal cohort of over 71,000 individuals exposed to the September 11, 2001, attacks in New York City. Established in response to concerns about long-term health consequences of the attacks, the Registry was designed to monitor the physical and mental health of those exposed, support research on emerging conditions, and help connect enrollees with services within the World Trade Center Health Program (World Trade Center Health Registry). The WTCHR has conducted five waves of survey data collection at approximately three- to four-year intervals, beginning with a baseline survey in 2003–04 and most recently with Wave 5 in 2020–21. Eligible participants included rescue and recovery workers; Lower Manhattan residents living south of

Canal Street; school children and staff; and building occupants or passersby south of Chambers Street (Murphy et al., 2007). Surveys collected information on demographics, 9/11-related exposures, and physical and mental health status. Study materials are publicly available online. The sample for the Wave 5 survey included 39,647 enrollees who had responded to at least three previous wave surveys (Wave 1, Wave 2, and Wave 3 and/or Wave 4), and enrollees who turned 18 years old after WTCHR enrolment. This analysis includes WTCHR enrollees who were aged 18 years or older on September 11, 2001, completed the Wave 5 survey, and responded to Wave 5 items about ACEs. A total of 26,178 individuals met these criteria.

2.2. Exposure variable—WTC disaster-related potentially traumatic experiences (PTE)

WTC disaster-related exposure was measured using the 12-item WTC exposure scale developed by Adams et al. (2006). This scale sums affirmative responses to a series of traumatic events that occurred during or immediately following the September 11, 2001 attacks. Participants reported whether they experienced each of the following: being inside the North or South WTC tower or another building that fully collapsed; witnessing three or more traumatic events (e.g., planes striking the towers, buildings collapsing, individuals being injured or killed, people jumping or falling, or crowds fleeing debris); fearing serious injury or death; losing a close family member, friend, or coworker; experiencing intense dust cloud exposure; sustaining damage to their workplace or home furnishings; sustaining a physical injury, participating in rescue or recovery efforts; being displaced from home for at least 24 h between September 11 and 18, 2001; or losing a job due to the attacks. Responses were summed to create a cumulative exposure score and categorized into four levels: none/low (0–1 exposures), medium (2–3), high (4–5), and very high (6–12) (Adams et al., 2006). This measure is referred to in the present study as WTC-related Potentially Traumatic Experiences (PTE) and reflects the intensity of exposure to traumatic events specifically related to the WTC disaster.

2.3. Outcome variables—symptoms of post-traumatic stress disorder, depression, and unhealthy drinking

Probable PTSD symptoms were assessed across all five WTCHR survey waves. Waves 1 through 4 used the PTSD Checklist—Specific Version (PCL-S), while Wave 5 used the PTSD Checklist for DSM-5 (PCL-5). The PCL-5 consists of 20 items assessing PTSD symptoms over the past 30 days, each rated on a scale from 0 (“not at all”) to 4 (“extremely”), yielding a total score ranging from 0 to 80. Participants with a total score of 33 or higher were classified as having probable PTSD. To ensure comparability across waves, PCL-S scores from Waves 1 through 4 were converted to PCL-5 equivalent scores using a validated crosswalk developed by Moshier et al. (Moshier et al., 2019). Participants were classified as having chronic probable PTSD if they met criteria for probable PTSD in at least three of the survey waves. As a secondary outcome, we also assessed prevalent probable PTSD, defined as meeting criteria for probable PTSD based on PCL-5 responses at Wave 5.

Symptoms of depression were assessed at Waves 3, 4, and 5 using the 8-item Patient Health Questionnaire (PHQ-8), a validated tool for screening depressive symptoms experienced over the past two weeks (Kroenke et al., 2009). At each wave, participants with a total score greater than or equal to 10 were classified as having moderate to severe depressive symptoms. Individuals were classified as having chronic depressive symptoms if they met this threshold at two or more of the three assessment waves (Kroenke et al., 2009). As a secondary outcome, we also assessed prevalent depressive symptoms, defined as moderate to severe depressive symptoms (PHQ-8 ≥ 10) at Wave 5.

Unhealthy drinking was assessed in Waves 2 through 5 using items adapted from the National Survey on Drug Use and Health (NSDUH). It was defined as consuming more than four drinks on the same occasion

for women, or more than five drinks on the same occasion for men, on at least one day in the past 30 days. Participants who met this definition at three or more of the four assessment waves were classified as engaging in chronic unhealthy drinking. As a secondary outcome, we also assessed prevalent unhealthy drinking, defined as meeting the unhealthy drinking threshold at Wave 5.

2.4. Modifier variable—adverse childhood experiences

Adverse Childhood Experiences (ACE) were assessed at Wave 5 using a 10-item measure capturing exposure to various forms of abuse, neglect, and household dysfunction experienced before age 18. Participants were asked whether they had experienced verbal abuse, physical abuse, sexual assault, emotional neglect, physical neglect, parental separation or divorce, witnessing maternal abuse, household substance use, household mental illness, or household incarceration. Affirmative responses were summed to create a total ACE score ranging from 0 to 10. For descriptive and analytic purposes, ACE scores were categorized into three groups: never (0 ACEs), low frequency (1–2 ACEs), and high frequency (3 or more ACEs).

2.5. Sociodemographic variables

Demographic covariates were measured at the Wave 1 survey and included age on September 11, 2001, sex, race/ethnicity, educational attainment, and marital status.

2.6. Statistical analysis

We examined descriptive characteristics of the analytic sample stratified by levels of WTC-related PTEs and ACEs using proportions and

chi-square tests. PTE and ACE were categorized into four and three levels, respectively. For Table 1, we calculated frequencies and column percentages for key demographic and health-related characteristics across PTE and ACE categories. For Table 2, we summarized the distribution of primary outcomes (chronic symptoms of probable PTSD, depression and unhealthy drinking) and secondary outcomes (prevalent symptoms of probable PTSD, depression, and unhealthy drinking at Wave 5) across the same exposure and modifier categories.

To assess whether the association between PTE and each outcome varied by ACE, we evaluated effect measure modification on both the multiplicative and additive scales. For each outcome—including chronic and prevalent symptoms of probable PTSD, depression, and unhealthy drinking—we fit a single Poisson regression model with robust standard errors including categorical variables for PTE and ACE, their interaction term, and covariates for age, sex, race/ethnicity, education, and marital status (Zou, 2004). Adjusted risk ratios (aRRs) and 95 % confidence intervals (CIs) were estimated for each joint level of PTE and ACE, using the doubly unexposed group (medium/low PTE and no ACEs) as the reference. The medium and low PTE categories were combined to form the reference group to provide a stable referent and align with the conceptual definition of a “doubly unexposed” group in joint exposure analyses. We also estimated associations between PTE and each outcome within strata of ACE to evaluate whether the effect of PTE differed across ACE levels. Multiplicative interaction was assessed by testing the statistical significance of the interaction term, while differences in stratum-specific aRRs informed interpretation of potential effect modification.

Additive interaction was assessed using the relative excess risk due to interaction (RERI), calculated as $RERI = RR_{11} - RR_{10} - RR_{01} + 1$, where RR_{11} represents the risk among those doubly exposed (e.g., high PTE and high ACE), RR_{10} and RR_{01} represent risk among those exposed to only one of the two factors, and RR_{00} is the reference group. RERI values and

Table 1

Cohort characteristics by WTC-related potentially traumatic experience(s) (PTE) and adverse childhood experience(s) (ACE), $N = 26,178$.

Baseline characteristic ^a	Overall N (%)	PTE (exposure), column %s				ACE (modifier), column %s		
		None/Low	Medium	High	Very high	Never	Low frequency	High frequency
Total	26,178 (100)	6354 (24.3)	11,128 (42.5)	6217 (23.7)	2479 (9.5)	14,300 (54.6)	7624 (29.1)	4254 (16.3)
Age on 9/11/01								
18–24	1115 (4.3)	291 (4.6)	526 (4.7)	228 (3.7)	70 (2.8)	619 (4.3)	318 (4.2)	178 (4.2)
25–44	13,819 (52.8)	2796 (44.0)	5973 (53.7)	3541 (57.0)	1509 (60.9)	7290 (51.0)	4053 (53.2)	2476 (58.2)
45–64	10,871 (41.5)	3074 (48.4)	4508 (40.5)	2403 (38.7)	886 (35.7)	6141 (42.9)	3160 (41.4)	1570 (36.9)
65+	373 (1.4)	193 (3.0)	121 (1.1)	45 (0.7)	14 (0.6)	250 (1.7)	93 (1.2)	30 (0.7)
Sex								
Male	16,214 (61.9)	3649 (57.4)	6714 (60.3)	4041 (65.0)	1810 (73.0)	9527 (66.6)	4537 (59.5)	2150 (50.5)
Female	9964 (38.1)	2705 (42.6)	4414 (39.7)	2176 (35.0)	669 (27.0)	4773 (33.4)	3087 (40.5)	2104 (49.5)
Race/ethnicity								
Hispanic	2698 (10.3)	537 (8.5)	1161 (10.4)	711 (11.4)	289 (11.7)	1226 (8.6)	841 (11.0)	631 (14.8)
Black, non-Hispanic	2297 (8.8)	547 (8.6)	1056 (9.5)	531 (8.5)	163 (6.6)	1117 (7.8)	732 (9.6)	448 (10.5)
White, non-Hispanic	19,274 (73.6)	4689 (73.8)	8112 (72.9)	4592 (73.9)	1881 (75.9)	10,807 (75.6)	5605 (73.5)	2862 (67.3)
Asian, non-Hispanic	1164 (4.5)	393 (6.2)	473 (4.3)	221 (3.6)	77 (3.1)	825 (5.8)	211 (2.8)	128 (3.0)
Other, non-Hispanic	745 (2.9)	188 (3.0)	326 (2.9)	162 (2.6)	69 (2.8)	325 (2.3)	235 (3.1)	185 (4.3)
Income ^b								
Less than \$25,000	1524 (5.8)	442 (7.7)	594 (5.9)	336 (5.9)	152 (6.6)	803 (6.2)	391 (5.6)	330 (8.3)
\$25,000– < \$50,000	4158 (15.9)	1216 (21.3)	1768 (17.4)	834 (14.6)	340 (14.8)	2063 (16.0)	1234 (17.6)	861 (21.7)
\$50,000– < \$75,000	5263 (20.1)	1399 (24.5)	2245 (22.1)	1161 (20.3)	458 (19.9)	2777 (21.5)	1613 (23.0)	873 (22.0)
\$75,000– < \$150,000	9724 (37.1)	2066 (36.1)	4101 (40.4)	2512 (44.0)	1045 (45.5)	5457 (42.3)	2814 (40.1)	1453 (36.6)
\$150,000+	3204 (12.2)	594 (10.4)	1443 (14.2)	865 (15.2)	302 (13.1)	1793 (13.9)	962 (13.7)	449 (11.3)
Marital status ^a								
Married or living with partner	17,849 (68.6)	4312 (68.3)	7520 (67.9)	4258 (68.8)	1759 (71.2)	10,211 (71.8)	5069 (66.8)	2569 (60.7)
Divorced or separated	2852 (11.0)	674 (10.7)	1189 (10.7)	705 (11.4)	284 (11.5)	1302 (9.2)	916 (12.1)	634 (15.0)
Widowed	421 (1.6)	114 (1.8)	170 (1.5)	95 (1.5)	42 (1.7)	230 (1.6)	109 (1.4)	82 (1.9)
Never married	4913 (18.9)	1212 (19.2)	2189 (19.8)	1127 (18.2)	385 (15.6)	2479 (17.4)	1490 (19.6)	944 (22.3)
Education ^a								
Less than high school	612 (2.3)	185 (2.9)	254 (2.3)	128 (2.1)	45 (1.8)	366 (2.6)	154 (2.0)	92 (2.2)
High school graduate/GED	4484 (17.2)	1037 (16.4)	1985 (17.9)	1036 (16.7)	426 (17.2)	2517 (17.7)	1225 (16.1)	742 (17.5)
Some college	6375 (24.5)	1352 (21.4)	2615 (23.6)	1624 (26.2)	784 (31.7)	3330 (23.4)	1915 (25.2)	1130 (26.7)
College graduate or above	14,586 (56.0)	3745 (59.3)	6224 (56.2)	3402 (55.0)	1215 (49.2)	8017 (56.3)	4298 (56.6)	2271 (53.6)

^a <1 % missing.

^b 9 % missing.

* All bivariate characteristics are statistically significantly different (Chi-Square p-value < 0.001).

Table 2Outcome variables by WTC-related potentially traumatic experience(s) (PTE) and adverse childhood experience(s) (ACE), $N = 26,178$.

Outcome variable ^a	Total N, %	PTE variable, exposure (N, column %)				ACE variable, modifier (N, column %)		
		None/Low	Medium	High	Very high	Never	Low Frequency	High Frequency
Total		6354 (24.3)	11,128 (42.5)	6217 (23.7)	2479 (9.5)	14,300 (54.6)	7624 (29.1)	4254 (16.3)
Primary outcomes								
Chronic PTSD ^a								
Yes	2157 (8.3)	142 (2.3)	673 (6.1)	769 (12.5)	573 (23.3)	869 (6.1)	596 (7.9)	692 (16.4)
No	23,824 (91.7)	6166 (97.7)	10,380 (93.9)	5394 (87.5)	1884 (76.7)	13,316 (93.9)	6972 (92.1)	3536 (83.6)
Chronic depression ^b								
Yes	3092 (12.1)	417 (6.7)	1183 (10.9)	933 (15.3)	559 (23.1)	1105 (7.9)	940 (12.6)	1047 (25.1)
No	22,533 (87.9)	5802 (93.3)	9705 (89.1)	5163 (84.7)	1863 (76.9)	12,883 (92.1)	6521 (87.4)	3129 (74.9)
Chronic unhealthy drinking ^a								
Yes	4019 (15.4)	641 (10.1)	1661 (15.0)	1170 (18.9)	547 (22.1)	2069 (14.5)	1232 (16.2)	718 (16.9)
No	22,113 (84.5)	5700 (89.9)	9449 (85.0)	5036 (81.1)	1928 (77.9)	12,202 (85.5)	6380 (83.8)	3531 (83.1)

^a <1 % missing.^b 2.1 % missing.^{*} All bivariate characteristics are statistically significantly different (Chi-Square p -value < 0.0001).

confidence intervals were derived using parameter estimates and covariances from the fitted model, computed using calculations provided by VanderWeele and Knol (VanderWeele and Knol, 2014). The table layout was guided by recommendations from the Knol and VanderWeele supplement for presenting interaction analyses involving categorical exposures (Knol and VanderWeele, 2012). This same modeling approach was applied separately for each of the primary and secondary outcomes: chronic probable PTSD, depression, and unhealthy drinking, and their corresponding Wave 5 (prevalent) measures. We used SAS v9.4 (SAS Institute, Cary, NC, USA) to perform statistical analyses.

The study was approved by the Institutional Review Board of the New York City Department of Health and Mental Hygiene (protocol code 02–058, approved 14 May 2020). Participant consent for survey participation was verbally obtained at study enrolment. The institutional review boards of both the Centers for Disease Control and Prevention and the New York City Department of Health and Mental Hygiene approved the WTCR protocol, including the use of data.

3. Results

3.1. Sample characteristics by PTE and ACE level

The analytic sample consisted of 26,178 participants. Most (82.4 %) participants participated in all five waves of data collection. WTC-related PTEs were distributed as follows: 24.3 % reported none or low exposure, 42.5 % medium, 23.7 % high, and 9.5 % very high exposure (Table 1). ACE were categorized as never (54.6 %), low frequency (1–2 ACEs, 29.1 %), and high frequency (3+ ACEs, 16.3 %). The most commonly reported ACEs were losing a parent through divorce, separation, or another reason (18.4 %), living with someone with a substance use disorder (17.5 %), and experiencing verbal abuse (15.8 %). Physical neglect was the least commonly reported ACE (3.3 %). Sociodemographic and health characteristics varied significantly across levels of both PTE and ACE ($p < 0.001$). Participants with very high PTE exposure were more likely to be male and aged 25–44 at the time of the attacks. Higher ACE frequency was associated with a greater proportion of female participants and individuals aged 25–44 and was less common among those identifying as White or Asian (non-Hispanic). Participants with high ACE exposure were also more likely to be unmarried.

3.2. Prevalence of outcomes by PTE and ACE level

Across the full sample, 8.3 % met criteria for chronic probable PTSD, 12.1 % for chronic depressive symptoms, and 15.4 % for chronic unhealthy drinking (Table 2). Chronic probable PTSD prevalence increased substantially with higher PTE and ACE exposure, from 2.3 % among those with none/low PTE to 23.3 % among those with very high PTE,

and from 6.1 % among those with no ACEs to 16.4 % among those with high ACEs. A similar pattern was observed for chronic depressive symptoms (ranging from 6.7 % to 23.1 % across PTE levels, and 7.9 % to 25.1 % across ACE levels) and for chronic unhealthy drinking (10.1 % to 22.1 % across PTE levels; 14.5 % to 16.9 % across ACE levels).

Secondary outcomes followed the same patterns. For example, prevalent probable PTSD at Wave 5 was reported by 10.2 % of participants overall but increased to 22.1 % among those with very high PTE and to 20.1 % among those with high ACE (Supplemental Table 1). Similar gradients were observed for prevalent depressive symptoms and unhealthy drinking. All bivariate associations between PTE/ACE and outcomes were statistically significant.

3.3. Effect measure modification for primary outcomes

3.3.1. Chronic probable PTSD

We observed a pattern of increasing risk of chronic probable PTSD with higher levels of both PTE and ACE exposure, indicating a compounding effect (Table 3). Compared to participants with neither exposure (i.e., medium/low PTE and no ACEs), those with high PTE and high ACE had an aRR of 6.76 (95 % CI: 5.77, 7.94), and those with very high PTE and high ACE had an aRR of 10.67 (95 % CI: 9.00, 12.65). Risk also increased with each exposure independently. Participants exposed to low and high ACEs in the absence of PTE exposure had aRRs of 1.45 (95 % CI: 1.23, 1.72) and 3.11 (95 % CI: 2.66, 3.64), respectively. Similarly, those with high and very high PTE exposure without ACEs had aRRs of 2.97 (95 % CI: 2.54, 3.47) and 6.78 (95 % CI: 5.81, 7.92), respectively. Additive interaction was observed between high ACE and high PTE exposures (RERI = 1.68, 95 % CI: 0.91, 2.45; $p < 0.01$), and between high ACE and very high PTE exposure (RERI = 1.78, 95 % CI: 0.45, 3.10; $p < 0.01$).

Associations between PTE and chronic probable PTSD varied by ACE level. Among individuals with no ACEs, the aRR for chronic probable PTSD was 2.97 (95 % CI: 2.54, 3.47) for high PTE and 6.78 (95 % CI: 5.81, 7.92) for very high PTE, relative to those with medium/low PTE. The magnitude of association attenuated with increasing ACE exposure: in the high ACE group, aRRs were 2.18 (95 % CI: 1.86, 2.54) for high PTE and 3.43 (95 % CI: 2.91, 4.05) for very high PTE. This pattern was consistent with evidence of multiplicative interaction, particularly for very high PTE, where interaction was statistically significant for both the low and high ACE exposure ($p < 0.01$ for both). For high PTE, significant interaction was observed with high ACE exposure ($p < 0.01$), but not low ACE exposure ($p = 0.49$).

3.3.2. Chronic depressive symptoms

Similarly, we observed a pattern of increasing risk of chronic depressive symptoms with higher exposure to both PTE and ACE

Table 3

Effect measure modification by adverse childhood experiences (ACE) on the association between WTC-related potentially traumatic experiences (PTE) and Chronic probable post-traumatic stress disorder (PTSD), on additive and multiplicative scales, $N = 25,981$.

		ACE level					
		Never		Low frequency		High frequency	
		N with & without chronic PTSD	aRR ^a (95 %CI)	N with & without chronic PTSD	aRR ^a (95 %CI)	N with & without chronic PTSD	aRR ^a (95 %CI)
PTE level	Medium or less	297/9293	1.0	228/4817	1.45 (1.23, 1.72)	290/2436	3.11 (2.66, 3.64)
	High	302/2996	2.97 (2.54, 3.47)	228/1585	3.94 (3.34, 4.65)	239/813	6.76 (5.77, 7.94)
	Very high	270/1027	6.78 (5.81, 7.92)	140/570	6.28 (5.22, 7.57)	163/287	10.67 (9.00, 12.65)
aRRs (95 %CI) for High PTE level within strata of ACE level			2.97 (2.54, 3.47)		2.71 (2.27, 3.23)		2.18 (1.86, 2.54)
aRRs (95 %CI) for Very High PTE level within strata of ACE level			6.78 (5.81, 7.92)		4.32 (3.56, 5.25)		3.43 (2.91, 4.05)
Measures of interaction on additive scale							
PTE level				Low frequency ACE (95 % CI, p)		High frequency ACE (95 % CI, p)	
High PTE				0.51 (−0.05, 1.08), <i>p</i> = 0.07		1.68 (0.91, 2.45), <i>p</i> < 0.01	
Very high PTE				−0.95 (−2.11, 0.20), <i>p</i> = 0.11		1.78 (0.45, 3.10), <i>p</i> < 0.01	
Measures of interaction on multiplicative scale							
PTE level				Low frequency ACE (95 % CI, p)		High frequency ACE (95 % CI, p)	
High PTE				0.92 (0.73, 1.16), <i>p</i> = 0.49		0.73 (0.59, 0.91), <i>p</i> < 0.01	
Very high PTE				0.64 (0.50, 0.82), <0.01		0.51 (0.40, 0.63), <i>p</i> < 0.01	

^a Adjusted for age, sex, race/ethnicity, education, and marital status.

Table 4

Effect measure modification by adverse childhood experiences (ACE) on the association between WTC-related potentially traumatic experiences (PTE) and chronic depression, on additive and multiplicative Scales, $N = 25,625$.

		ACE level					
		Never		Low frequency		High frequency	
		N with & without chronic depression	aRR ^a (95 % CI)	N with & without chronic depression	aRR ^a (95 % CI)	N with & without chronic depression	aRR ^a (95 % CI)
PTE level	Medium or less	532/8913	1.0	504/4467	1.78 (1.58, 2.00)	564/2127	3.44 (3.07, 3.84)
	High	334/2934	1.78 (1.56, 2.03)	293/1494	2.83 (2.47, 3.24)	306/735	4.86 (4.29, 5.52)
	Very high	239/1036	3.31 (2.87, 3.81)	143/560	3.47 (2.93, 4.11)	177/267	6.39 (5.54, 7.37)
aRRs (95 %CI) for High PTE level within strata of ACE level			1.78 (1.56, 2.03)		1.59 (1.39, 1.82)		1.42 (1.26, 1.59)
aRRs (95 %CI) for Very High PTE level within strata of ACE level			3.31 (2.87, 3.81)		1.96 (1.65, 2.31)		1.86 (1.62, 2.13)
Measures of interaction on additive scale							
PTE level				Low frequency ACE (95 % CI, p)		High frequency ACE (95 % CI, p)	
High PTE				0.27 (−0.09, 0.63), <i>p</i> = 0.14		0.64 (0.17, 1.12), <i>p</i> < 0.01	
Very high PTE				−0.61 (−1.25, 0.04), <i>p</i> = 0.06		0.64 (−0.09, 1.37), <i>p</i> = 0.08	
Measures of interaction on multiplicative Scale							
PTE level				Low frequency ACE (95 % CI, p)		High frequency ACE (95 % CI, p)	
High PTE				0.89 (0.74, 1.08), <i>p</i> = 0.24		0.79 (0.67, 0.95), <i>p</i> = 0.01	
Very high PTE				0.59 (0.48, 0.74), <i>p</i> < 0.01		0.56 (0.46, 0.68), <i>p</i> < 0.01	

^a Adjusted for age, sex, race/ethnicity, education, and marital status.

(Table 4). Compared to participants with neither exposure, those with high PTE and high ACE exposures had an aRR of 4.86 (95 % CI: 4.29, 5.52), and those with very high PTE and high ACE exposures had an aRR of 6.39 (95 % CI: 5.54, 7.37). Risk also increased with each exposure independently. Participants exposed to high or very high PTE without ACE exposure had aRRs of 1.78 (95 % CI: 1.56, 2.03) and 3.31 (95 % CI: 2.87, 3.81), respectively. Similarly, participants with medium/low PTE exposure but with low or high ACE exposure had aRRs of 1.78 (95 % CI: 1.58, 2.00) and 3.44 (95 % CI: 3.07, 3.84), respectively. For high PTE, significant additive interaction was observed with high ACE exposure, but not with low ACE exposure. No evidence of interaction on the

additive scale was observed in the very high PTE group.

Associations between PTE and chronic depressive symptoms varied by ACE level. Among individuals with no ACEs, the aRR for chronic depressive symptoms was 1.78 (95 % CI: 1.56, 2.03) with high PTE exposure and 3.31 (95 % CI: 2.87, 3.81) with very high PTE exposure, relative to those with medium/low PTE exposure. The magnitude of association attenuated with increasing ACE exposure: in the high ACE group, aRRs were 1.42 (95 % CI: 1.26, 1.59) for high PTE and 1.86 (95 % CI: 1.62, 2.13) for very high PTE. This pattern was consistent with evidence of multiplicative interaction, particularly for very high PTE, where interaction was statistically significant for both low and high ACE

exposure ($p < 0.01$). For high PTE, significant interaction was observed with high ACE exposure ($p < 0.01$), but not low ACE exposure ($p = 0.24$).

3.3.3. Chronic unhealthy drinking

Risk of chronic unhealthy drinking also increased with higher levels of both PTE and ACE, though associations were more modest (Table 5). Compared to participants with neither exposure, those with high PTE and high ACE had an aRR of 1.52 (95 % CI: 1.33, 1.74), and those with very high PTE and high ACE had an aRR of 1.69 (95 % CI: 1.42, 2.02). Risk also increased with each exposure independently. Participants with high or very high PTE and no ACE exposure had aRRs of 1.42 (95 % CI: 1.30, 1.55) and 1.42 (95 % CI: 1.26, 1.59), respectively. Those with no PTE beyond medium/low levels but with low or high ACE exposure had aRRs of 1.19 (95 % CI: 1.10, 1.30) and 1.34 (95 % CI: 1.21, 1.48), respectively. There was no evidence of additive interaction, as RERI estimates were small and not statistically significant in any ACE group.

Associations between PTE and chronic unhealthy drinking showed some variation by ACE level. Among individuals with no ACEs, the aRR was 1.42 (95 % CI: 1.30, 1.55) for high PTE and 1.42 (95 % CI: 1.26, 1.59) for very high PTE. Among those with high ACEs, aRRs were slightly lower: 1.14 (95 % CI: 0.98, 1.32) for high PTE and 1.26 (95 % CI: 1.04, 1.53) for very high PTE. Multiplicative interaction was observed for high PTE with both low and high ACE exposure (interaction $p = 0.04$ and $p = 0.01$, respectively), though not for very high PTE.

3.4. Supplementary analyses of prevalent outcomes

Results for the secondary outcomes—prevalent symptoms of PTSD, depression, and unhealthy drinking—were largely consistent with those observed for the chronic outcomes (Supplementary Tables 2–4), with risk increasing with greater exposure to both PTE and ACE, and the highest risk observed among individuals exposed to both. For symptoms of PTSD and depression, findings were consistent across chronic and prevalent outcomes, with evidence of multiplicative interaction and attenuation of relative risks at higher ACE levels, particularly for very high PTE ($p < 0.01$). Additive interaction was also observed for PTSD symptoms in the high ACE group in both chronic and prevalent models. In contrast, results for unhealthy drinking differed: while there was

evidence of multiplicative interaction for the chronic outcome, no evidence of interaction was observed for the prevalent unhealthy drinking outcome on either scale.

4. Discussion

Among this sample of WTC-exposed individuals, chronic symptoms of PTSD, depression, and unhealthy drinking were reported by 8 %, 12 %, and 15 % of respondents approximately 20 years after exposure to the WTC attacks. This is consistent with previous research within this population that has found elevated prevalence of these symptoms up to 15 years after the WTC attacks (Bromet et al., 2016; Hamwey et al., 2020; Jordan et al., 2019; Welch et al., 2014). Consistent with prior research, both adverse childhood experiences and WTC-related PTE exposure were independently related to persistent mental health symptoms assessed (Liu et al., 2014; Mukherjee et al., 2020; Takemoto et al., 2021). Importantly, compared to medium or no WTC-related PTE exposure, high and very high WTC-related PTE exposure were associated with significantly increased risk of chronic symptoms of depression, PTSD, and unhealthy drinking across all levels of ACE exposure, including among those reporting no ACE exposure. Such findings highlight the critical importance of integrating mental health screening and treatment into core components of evidence-based health care following a mass casualty or terror event. Ensuring early access to evidence-based mental health screening and treatment may foster early identification of individuals experiencing mental health challenges and reduce the development of chronic mental health conditions among survivors.

There was evidence of additive and multiplicative interaction by ACE exposure of the relationship between WTC-related PTE exposure and persistent symptoms of probable PTSD. However, the directionality of interaction differed based on the scale of interaction assessed. On the additive scale there was evidence of positive effect measure modification, while on the multiplicative scale, there was evidence of negative effect measure modification. Such differences in directionality are not uncommon because the additive and multiplicative scales capture different dimensions of joint effect. That is, the additive scale reflects absolute risk differences (biologic interaction or excess risk due to joint exposure), whereas the multiplicative scale reflects relative differences in effect. In our study, the positive additive interaction suggests that

Table 5

Effect measure modification by adverse childhood experiences (ACE) on the association between WTC-related potentially traumatic experiences (PTE) and chronic unhealthy drinking, on additive and multiplicative scales, $N = 26,132$.

		ACE level					
		Never		Low frequency		High frequency	
		N with & without chronic unhealthy drinking	aRR ^a (95 % CI)	N with & without chronic unhealthy drinking	aRR ^a (95 % CI)	N with & without chronic unhealthy drinking	aRR ^a (95 % CI)
PTE level	Medium or less	1170/8473	1.0	712/4357	1.19 (1.10, 1.30)	420/2319	1.34 (1.21, 1.48)
	High	631/2690	1.42 (1.30, 1.55)	343/1484	1.45 (1.31, 1.62)	196/862	1.52 (1.33, 1.74)
	Very high	268/1039	1.42 (1.26, 1.59)	177/539	1.74 (1.52, 2.00)	102/350	1.69 (1.42, 2.02)
aRRs (95 %CI) for High PTE level within strata of ACE level			1.42 (1.30, 1.55)		1.22 (1.08, 1.36)		1.14 (0.98, 1.32)
aRRs (95 %CI) for Very High PTE level within strata of ACE level			1.42 (1.26, 1.59)		1.46 (1.26, 1.69)		1.26 (1.04, 1.53)
Measures of interaction on additive scale							
PTE level				Low frequency ACE (95 % CI, p)		High frequency ACE (95 % CI, p)	
High PTE				−0.16 (−0.35, 0.03), <i>p</i> = 0.10		−0.23 (−0.48, 0.01), <i>p</i> = 0.06	
Very high PTE				0.13 (−0.14, 0.40), <i>p</i> = 0.34		−0.07 (−0.40, 0.27), <i>p</i> = 0.69	
Measures of interaction on multiplicative scale							
PTE level				Low frequency ACE (95 % CI, p)		High frequency ACE (95 % CI, p)	
High PTE				0.86 (0.74, 0.99), <i>p</i> = 0.04		0.80 (0.67, 0.95), <i>p</i> = 0.01	
Very high PTE				1.03 (0.86, 1.24) <i>p</i> = 0.76		0.89 (0.71, 1.11), <i>p</i> = 0.30	

^a Adjusted for age, sex, race/ethnicity, education, and marital status.

individuals with ACEs experienced a greater *absolute* increase in PTSD prevalence when also exposed to WTC-related PTEs compared to those without ACEs. Conversely, the negative multiplicative interaction indicates that the *relative* effect of WTC-related PTEs on PTSD symptomatology was smaller among those with vs without ACEs—consistent with a higher baseline susceptibility that diminishes the relative contrast. Together, these findings imply that ACEs and WTC-related PTEs act synergistically in *absolute* terms to elevate risk, even if the *proportional* increase in risk associated with WTC-related PTEs is attenuated among individuals with childhood adversity.

Prior research into the relationship among childhood adversity, traumatic exposure in adulthood, and long-term mental health symptoms remains limited. However, research with WTC responders found that having been bullied in childhood increased the odds of probable PTSD after WTC exposure (Mukherjee et al., 2020). Research with a U.S. national sample of individuals with no history of psychiatric disorders prior to the WTC attack found that the risk of WTC-related internalizing and externalizing symptomatology was greater among who had (vs had not) experienced child maltreatment (Meyers et al., 2015). Individuals who experienced childhood adversity may warrant enhanced mental health screening, treatment, or referral to care following subsequent PTE exposure. Trauma assessments following PTE in adulthood should include comprehensive assessments of prior trauma throughout the life course, including experiences in childhood. Comprehensive PTE screening that includes screening for ACEs may help identify individuals at risk for prevalent and persistent PTSD.

Importantly, these findings highlight the persistent mental health impact of adverse childhood experiences and reinforce the critical importance of primary prevention of childhood adversity and ACE exposure (Steverman and Shern, 2017). Future research should examine the extent to which early identification of ACE exposure and timely receipt of evidence-based mental health care in childhood or adolescence influences the mental health impact of subsequent PTE exposure, potentially through fostering resilience or adaptive coping strategies. Strategies to prevent child abuse and maltreatment and to support children experiencing adversity have the potential to improve mental health throughout the life course.

Mechanisms through which childhood adversity increases the risk of long-term PTSD symptoms after adult PTE exposure should be explored. One pathway through which prior PTE exposure may increase the severity and persistence of mental health symptoms of subsequent PTE exposure is through stress sensitization (Davis et al., 2023; Meyers et al., 2015; Shao et al., 2015). The stress sensitization hypothesis posits that early traumatic exposures increase vulnerability to subsequent traumatic exposures (Davis et al., 2023; Kim et al., 2023). Specifically, childhood adversity may compromise one's capacity to adequately regulate stress (Kim et al., 2023). Thus, subsequent PTE exposure or life stress may produce a greater stress response, greater difficulty managing stress, and more severe or persistent PTSD symptoms (Shao et al., 2015). Alternately, it has also been posited that the cumulative burden of childhood and adult trauma may influence resilience and one's emotional regulation or capacity to manage subsequent traumatic exposures which, in turn, influences the severity and persistence of mental health symptoms (Demir et al., 2020; Watters et al., 2023; Zhao et al., 2022). Childhood adversity may increase the likelihood of disrupted attachment or social support mechanisms or maladaptive coping which may influence one's risk and resilience following PTE exposure in adulthood (Crow et al., 2021; Fares-Otero et al., 2023). Future research should the extent to which current findings are similar among adults who experienced other types of PTE exposure in adulthood, including more commonly occurring types of PTE exposure such as interpersonal violence, natural disasters, illness, and loss.

There was also evidence of multiplicative and additive interaction by ACE exposure of the relationship between WTC-related PTE exposure and persistent depressive symptoms. Like our PTSD findings, the directionality of interaction differed based on the scale of interaction

assessed. That is, the relative risk of persistent depressive symptoms following WTC-related PTE exposure was greater among those with high (vs low or no) ACE exposure. However, associations between WTC-related PTE and persistent depressive symptoms were attenuated among those with high ACE exposure compared to those with low or no ACE exposure. While PTSD is the most common mental health disorder studied in relation to trauma, growing evidence has found a relationship between traumatic exposure, including WTE-related exposure, and depression (Wang et al., 2023; Zvolensky et al., 2015). Prior research has found that almost one in four (24 %) children or adolescents exposed to trauma experience depressive symptoms, and that traumatic exposure was associated with greater odds of depressive symptoms (Vibhakkar et al., 2019). Importantly, a systematic review and meta-analysis found that evidence-based psychological and pharmacological treatments for depression were similarly effective in individuals with and without a history of childhood trauma, reinforcing the importance of screening and timely referral to evidence-based mental health care (Kuzminskaite et al., 2022). Pathways through which childhood adversity moderates the relationship between WTC-related PTE exposure and depressive symptoms should be explored. Prior research suggests that emotion regulation and maladaptive coping strategies may mediate the pathways between child trauma and depression severity and persistence (Hopfinger et al., 2016; Huh et al., 2017). The extent to which such pathways are influenced by PTE exposure in adulthood remains largely unexplored. Emerging evidence suggests that resilience and stress may influence the relationship between PTE exposure in childhood and adulthood depression (Wingo et al., 2010; Zheng et al., 2022). The extent to which these pathways differ among those exposed to a terror or mass trauma event warrants further investigation.

ACE exposure and WTC-related PTE exposure were both independently associated with persistent unhealthy drinking, though the magnitude of these associations were more modest compared to symptoms of depression or PTSD. There was no evidence of additive interaction by ACE exposure of the relationship between WTC-related PTE exposure and persistent unhealthy drinking. There was negative multiplicative interaction by ACE exposure of the relationship between WTC-related PTE exposure and persistent unhealthy drinking among those with high, but not very high WTC-related PTE exposure. Taken together, in contrast to our findings with symptoms of PTSD and depression, ACE exposure and WTC-related PTE exposure appear to largely influence the risk of persistent unhealthy drinking independently, rather than synergistically. Prior research into the influence of ACE exposure on the relationship between subsequent PTE exposure in adulthood and unhealthy drinking remains limited. However, our findings are consistent with prior research supporting a positive relationship between childhood adversity and alcohol use disorder and between WTC-related exposure and alcohol use (Boscarino et al., 2006; Fetzner et al., 2011).

Future research should examine the relationships among ACE exposure, PTE exposure in adulthood, and unhealthy drinking among those with and without comorbid PTSD, as prior research suggests that the relationships between childhood adversity and unhealthy drinking may differ by the presence of PTSD. Prior research has found that childhood trauma moderated the relationship between PTSD symptoms and alcohol use (Garrison-Desany et al., 2024). Integrated interventions that address trauma-related symptoms and unhealthy drinking may be particularly relevant for individuals with a history of trauma throughout the life course (Brady and Back, 2012). Findings reinforce the importance of assessing trauma throughout the life course among individuals with unhealthy drinking.

This study has limitations worth noting. First, our sample was limited to individuals who were impacted by the WTC attack and may not be generalizable to individuals who experienced other forms of terror or mass trauma or other types of PTE. In addition, our sample was comprised of individuals who participated in Wave 5 of the WTCR, as this was when ACE exposure was first assessed. It is possible that individuals with more persistent or severe mental health symptoms were

more likely to be lost to follow up in subsequent waves of WTC data collection. Supplemental Table 5 compares sociodemographic and mental health characteristics of Wave 1 participants and our Wave 5 analytic sample. Overall, it appears that those with probable PTSD at Wave 1 were *more* likely to be lost to follow-up, while those with higher WTC-related PTEs were *less* likely to be lost to follow-up. We hypothesize that this would bias PTE-PTSD associations toward the null. However, it remains unclear the influence that this pattern of loss to follow up would have on our modification questions of interest. Further, ACE exposure was collected after the WTC attacks, potentially influencing accuracy of ACE reporting and recall bias. Finally, the current analysis assessed the frequency of ACE exposure, but did not assess differences in effect measure modification by ACE type.

Despite these limitations, this study examined the influence of ACE exposure on the relationship between WTC-related PTE exposure and persistent and prevalent symptoms of PTSD, depression, and unhealthy drinking. Our findings suggest that childhood adversity and WTC-related PTE exposure positively interact on the additive scale to increase the risk of persistent PTSD and depressive symptoms. This reinforces the importance of comprehensive trauma screening, including for childhood adversity among adults with PTE exposure. Primary prevention of childhood adversity is an important public health priority that will improve the mental health of individuals throughout the life course.

CRedit authorship contribution statement

Angela M. Parcesepe: Methodology, Conceptualization, Writing – original draft. **Jenna Sanborn:** Methodology, Formal analysis, Data curation, Writing – original draft. **Julia S. Sisti:** Project administration, Writing – review & editing. **Janna Metzler:** Supervision, Writing – review & editing.

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Declaration of competing interest

The authors declare that they have no competing interests.

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Appendix A. Supplementary data

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