



# Longitudinal trajectories of binge and heavy drinking pattern among World Trade Center Health Registry enrollees, 2006–2021: A dual trajectory modeling approach

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## ABSTRACT

**Background:** This study examined drinking trajectories among World Trade Center Health Registry enrollees and evaluated potential risk factors.

**Methods:** A longitudinal study analyzing binge and heavy drinking trajectories over 15 years, involving 18,332 enrollees aged 18 or older on 9/11/2001, with 62.7 % identifying as male. Group-based trajectory modeling explored binge drinking and heavy drinking trajectories. Multinomial logistic regression was used to assess risk factors (9/11-exposure, rescue/recovery worker, 9/11-related post-traumatic stress disorder (PTSD), lack of social support) associated with these drinking trajectories. Dual trajectory analysis estimated the conditional probabilities between binge and heavy drinking group memberships. Trajectory models stratified by age group and sex, separately, were also examined.

**Findings:** Four trajectories described binge (very-low-stable (72.5 %), moderate-increasing (6.9 %), high-decreasing (11.8 %), and very-high-decreasing (8.8 %)) and heavy (very-low-stable (82.9 %), low-increasing (6.0 %), high-decreasing (5.9 %), and high-increasing (5.1 %)) drinking over time. In dual trajectory analyses, most binge drinking trajectories overlapped with similar heavy drinking trajectories. Individuals aged 36–64, non-Hispanic White, or experienced 9/11-related PTSD were more likely to follow the other binge drinking trajectories and the initially “high-” heavy drinking trajectories than their respective very-low-stable trajectories; females were more likely to follow “increasing” heavy drinking trajectories, while males were more likely to follow high or increasing binge trajectories. Compared to younger enrollees (36–54, 55–69 years of age), a higher proportion of those aged 70 + were in low-stable binge and heavy drinking trajectory groups.

**Conclusions:** The observed trajectory groups and factors associated with longitudinal patterns of excessive drinking may assist with developing targeted interventions like behavioral counseling.

## 1. Introduction

In the past two decades the United States (U.S.) has experienced a dramatic increase in deaths related to excessive drinking. The Centers for Disease Control and Prevention (CDC) reported a 29.3 % increase in deaths from 2016 to 2017–2020–2021 (137,927 vs 178,307, respectively) (Data on Excessive Drinking, 2024; Esser et al., 2024). Excessive consumption of alcohol, such as binge drinking (consuming large amounts in a short period), heavy drinking (consistently exceeding the recommended limit), underage drinking, and drinking during pregnancy may increase the risk of adverse health outcomes, fatal injury risks, and socioeconomic crises, with excessive consumption over time potentially

resulting in the development of alcohol use disorder (AUD) (Alpert et al., 2022; Data on Excessive Drinking, 2024; Rehm, 2011; Understanding Alcohol Use Disorder, 2020). The two primary excessive alcohol consumption behaviors, binge drinking and heavy drinking, were more common among males, 18–34 years old, and non-Hispanic White in the U.S., 2011–2017 (Azagba et al., 2020). In 2022, among the U.S. adult population, 53.4 % reported having at least one drink of alcohol within the past 30 days, the prevalence of binge drinking was 17.0 %, and the prevalence of heavy drinking was 6.9 % (BRFSS Prevalence & Trends Data, 2015; Data on Excessive Drinking, 2024; Drinking Levels and Patterns Defined, 2024). Similar to the general U.S. population, in New York State, the prevalence of binge drinking was 16.6 % and considerably

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lower for heavy drinking (6.1 %) (BRFSS Prevalence & Trends Data, 2015).

The September 11, 2001 (9/11) terrorist attacks on the World Trade Center (WTC) had far-reaching consequences for the health and well-being of those directly affected (Brackbill et al., 2009). Elevated prevalence of post-traumatic stress disorder (PTSD) has been observed among those affected (Brackbill et al., 2009), can be linked to a high level of psychological stress, and is a well-recognized psychiatric comorbidity following any major traumatic disaster (Neria et al., 2011). PTSD is commonly correlated with substance use disorder (SUD) (Roberts et al., 2016), including AUD, with approximately two-thirds of individuals with PTSD developing co-occurring SUD, either concurrently with or after the onset of PTSD (van Minnen et al., 2015). Individuals may exhibit an increased tendency to consume alcohol in an effort to cope with PTSD symptoms (Luciano et al., 2022). Aside from PTSD, exposure to 9/11 events, such as witnessing buildings collapse, fear of being killed or having a loved one killed, and dust cloud exposure, were linked to excessive alcohol use (Welch et al., 2014, 2017). Furthermore, various studies reported increased exposure to these unparalleled events resulting in a loss of social support due to self-imposed social isolation and unwillingness to participate in any entertainment (Gargano et al., 2016), making individuals (especially males) vulnerable towards excessive alcohol use (Fang and Lung, 2022).

Numerous studies have reported exposure to the 9/11 terrorist attacks as strongly associated with an increase in alcohol usage across diverse exposed populations, including Fire Department of New York (FDNY) members (Berninger et al., 2010), rescue and recovery workers (RRW), lower Manhattan residents, and passersby (Welch et al., 2014, 2017). Likewise, many other catastrophes have been associated with increased alcohol intake across various populations, such as survivors of the 2004 Southeast Asia tsunami (Nordlokken et al., 2013), 2010 Haiti earthquake (Ingalls, 2016), and Hurricanes Rita and Katrina (Cerdeira et al., 2011). However, there are differing opinions on whether disaster exposure has always been interlinked with disproportionate alcohol intake. An article among a multiple disasters-exposed population found that disaster(s) may not always lead into new onset post-disaster excessive alcohol use and dependence, but rather present as a continuation or recurrence of a pre-existing behavior (North et al., 2011), while others suggest increases in alcohol use may return to pre-disaster level over time (Ustoy et al., 2023). No study has examined the persistence of excessive alcohol use among a 9/11-exposed survivor population. Hence, it is vital to explore whether increased alcohol consumption persists more than 20 years after 9/11. This understanding can provide insights into the disaster's long-term effects on survivors and their tendencies toward excessive drinking and eventually AUD, necessitating medical treatment (Understanding Alcohol Use Disorder, 2020). Such insights may inform both individual-level and policy-level interventions.

In the present study, we aimed to investigate the trajectories of binge and heavy drinking behaviors among 9/11 survivors, and the relationships between the trajectories of these two contemporaneous excessive drinking behaviors.

## 2. METHODOLOGY

### 2.1. Data source

The WTC Health Registry ("Registry"), a longitudinal study of 71,423 individuals directly exposed to the 9/11 disaster, is used to track the physical and mental health impacts of this event and address gaps in care for 9/11-related health problems (Brackbill et al., 2009; Farfel et al., 2008). Individuals present in Lower Manhattan on 9/11, RRW, lower Manhattan residents, passersby, area workers, and students and staff from schools south of Canal Street were enrolled into the Registry with a baseline interview (Wave 1) conducted in 2003–2004; more details about recruitment are published elsewhere (Farfel et al., 2008). Four subsequent survey waves were conducted in 2006–2007 (Wave 2),

2011–2012 (Wave 3), 2015–2016 (Wave 4), and 2020–2021 (Wave 5). The Registry was approved by the New York City Department of Health and Mental Hygiene and the CDC's Institutional Review Boards.

### 2.2. Binge and heavy drinking trajectory

The key outcomes of interest were drinking trajectory patterns using data from Waves 2–5 (2006–2021). Participants were asked to self-report alcohol consumption within the last 30 days, including the number of days they had at least one drink, the average number of drinks consumed on those days (Waves 2–5), the number of times they had  $\geq 5$  drinks (Wave 2), and the number of times they had  $\geq 4$  (female) or  $\geq 5$  (male) drinks on one occasion (Waves 3–5).

Based on the National Institute on Alcohol Abuse and Alcoholism (NIAAA) criteria (Data on Excessive Drinking, 2024; *Drinking Levels and Patterns Defined*, 2024), binge drinking (yes/no) was defined at Waves 3–5 as consuming at least  $\geq 5$  drinks for males and  $\geq 4$  drinks for females on one occasion within the last 30 days of their survey. However, for all participants in Wave 2, binge drinking was having at least  $\geq 5$  drinks on one occasion within last 30-days. Heavy drinking was defined using both the NIAAA and Substance Abuse and Mental Health Services Administration (SAMHSA) criteria (Data on Excessive Drinking, 2024; *Drinking Levels and Patterns Defined*, 2024), with heavy drinking (yes/no) defined at Waves 2–5 as consuming  $\geq 15$  drinks per week for men and  $\geq 8$  drinks for women (NIAAA), or reporting  $\geq 5$  binge drinking episodes within the last 30 days (SAMHSA) of their survey.

### 2.3. Study sample

The study was limited to adult enrollees who were 18 years or older on 9/11/01 and completed all survey waves ( $n = 22,894$ ). After excluding enrollees who were missing responses to the alcohol questions in any of the follow-up surveys ( $n = 4562$ ), the final study sample consisted of 18,332 enrollees. While the legal drinking age in the U.S. is 21, we included participants aged 18 or older on 9/11, consistent with prior Registry studies and to maintain sample size for long-term follow-up.

### 2.4. Predictors and covariates

The 9/11-exposure summary score measure (Adams et al., 2006) has been shown to be associated with frequent binge drinking (Welch et al., 2014, 2017), mental health status, and unmet mental health care needs among Registry enrollees (Brackbill et al., 2013). This count captures exposure to 12 events assessed at Wave 1 or 2: presence in the North or South WTC tower or other collapsed buildings on 9/11; witnessed  $\geq 3$  events (airplane crashing into the towers, buildings collapsing, people falling/jumping from buildings, people injured/killed, or people running from a cloud of smoke); thought they may be injured or killed on 9/11; lost a relative on 9/11; lost a friend or acquaintance on 9/11; lost a coworker on 9/11; intense dust cloud exposure; damage to workplace or workplace furnishing or had to replace furniture in home; sustained an injury (broken bone, cut, concussion, burn, or sprain); involved in rescue or recovery work; evacuated one's home for at least 24 h between 9/11 and 9/18; and lost one's job because of 9/11. Based on the distribution (mean = 2.45, SD = 1.81; median = 2; range = 0–9), exposure levels were categorized as low/none (0–2), moderate (3–4), or high ( $\geq 5$ ).

The study assessed the lack of social support in Waves 3–5 using the Medical Outcomes Study (MOS) Modified Social Support Survey (MSSS-5), which included five questions regarding perception of help from others: availability of someone to take them to a doctor when needed, have a good time with, hug them, prepare their meals if unable to do so themselves, and understand their problems (Ritvo PG et al., 1997). Enrollees were asked to rate each item on a five-point scale from 1 = none of the time to 5 = all of the time. Responses to all five items

were summed for each wave to produce a raw score (range 5–25) which was transformed to a score of 0–100 (Ritvo PG et al., 1997). Enrollees with a transformed score < 55 at least one wave were considered lacking social support.

Ever having 9/11-related PTSD was determined using the 17-item PTSD Checklist-Specific (PCL-S) based on the Fourth Edition of the Diagnostic and Statistical Manual for Mental Disorders (DSM-IV) on Waves 2–4 and the 20-item PTSD Checklist for the Fifth Edition (DSM-V) (PCL-5) on Wave 5 (Weathers et al., 2023; Wilkins et al., 2011). For this study, the Waves 2–4 PCL scores were transformed to the DSM-V scale and converted to scores ranging from 0 to 80 (Moshier et al., 2019). A cutoff score of 33 was used to identify the presence of PTSD symptoms at Waves 2–5. Enrollees who had PTSD symptoms in at least one wave were considered to ever have 9/11-related PTSD (Weathers et al., 2023).

Enrollees who worked at least one shift at the WTC site, the WTC Recovery Operation on Staten Island, or on a barge between September 12, 2001, and June 30, 2002, were considered to be RRW; all others were non-RRW (Jordan et al., 2011).

Sociodemographic covariates used in the multivariate analyses to explore the association of the exposures of interest mentioned above with the binge and heavy drinking trajectories included age at Wave 5 (36–54, 55–69, ≥70), sex (male, female), and race/ethnicity (non-Hispanic White, non-Hispanic Black, non-Hispanic Other, Hispanic).

## 2.5. Data analysis

Descriptive analyses were conducted to explore the prevalence of binge and heavy drinking, sociodemographic factors, and predictors of interest. Next, group-based trajectory modeling (GBTM) was utilized to identify distinct trajectories of group memberships among enrollees with similar binge and heavy drinking patterns over fifteen years from Waves 2–5 (Nagin, 2005; Nguena Nguetack et al., 2020). Each of the model outputs identified the optimal number of unique trajectory groups and shapes and the approximate percentage of the population that falls within each group (Nagin, 2005). The logistic (LOGIT) model using PROC TRAJ macro was used to test the binary binge and heavy drinking outcome variables, initially using a one-class model and gradually increasing classes to identify the maximum number of subgroups. Enrollees were placed in the group with the highest likelihood of membership (Andruff H et al., 2009; Nagin, 2005). To determine the ideal number of groups and shape of trajectory models, the researchers compared the sample size-adjusted Bayesian information criterion (SAS-BIC), group sizes, and average posterior probabilities (AVP) (Andruff H et al., 2009; Nguena Nguetack et al., 2020). Quadratic shape trajectory model was initially used, but due to non-convergence across all four groups, linear trajectories were employed as needed (Andruff H et al., 2009). AVP measured enrollees' likelihood of belonging to each of the model trajectory groups, with a recommended value of ≥ 70 % for each subgroup (Andruff H et al., 2009). The final models were chosen based on parsimony, interpretability, and knowledge of our sample (Andruff H et al., 2009; Nagin, 2005).

Preliminary results suggested four-group trajectory models for both binge and heavy drinking behaviors, with the majority of enrollees exhibiting very-low-stable drinking behavior over time. Multinomial logistic regression was performed to compare the probability of membership in the other three groups compared to the very-low-stable group, adjusting for all predictors and covariates. We constructed two separate models, one for binge drinking and another for heavy drinking trajectories, with each model simultaneously adjusting for all included predictors. To address missing covariates' data, multiple imputation was performed using PROC MI with five imputations per model. The imputed datasets were analyzed separately and pooled using PROC MIANALYZE to produce final estimates (Little and Rubin, 2019).

Dual/joint GBTM was then performed to explore the relationships between binge drinking and heavy drinking (Andruff H et al., 2009; Graziane et al., 2016; Nagin, 2005; Nagin et al., 2018). These models

maximize the joint likelihood function, specifying both sets of trajectories simultaneously. The dual trajectory model outputs are comparable to univariate models, including the ideal number of trajectory groups and shapes and estimating the percentage of each group membership linking the two sets of trajectories (Nagin, 2005). Additionally, the dual models provide estimates of joint and conditional probabilities of binge and heavy trajectory group membership (Graziane et al., 2016). The study examined the probabilities of joint heavy and binge drinking group memberships, confirming their statistical significance using least square means and chi-square tests. We also performed stratified trajectory analyses by sex (11,501 male and 6831 female) to identify differences in group memberships among male and female participants in the study. All analyses were performed using SAS (version 9.4).

## 3. Results

Among 18,332 enrollees, most were non-Hispanic White (76.2 %), and male (62.7 %)(Table 1). Over half (51.4 %) were aged 55–69 at Wave 5, while one-quarter (25.2 %) were aged 36–54, and 23.4 % were 70 years of age or above. The sample was evenly distributed between RRW (48.0 %) and non-RRW (52.0 %). Nearly half had moderate to high 9/11-related exposure (45.0 %), 35.9 % ever lacked social support, and 23.9 % ever had 9/11-related PTSD symptoms. Approximately 42.2 % reported binge drinking and 24.1 % reported heavy drinking within the last 30 days of any of their four follow-up survey waves (Table 2). An overall decreasing trend in prevalence was observed for both binge and heavy drinking from Wave 2 to Wave 5.

Four distinct trajectory groups best described both binge and heavy

**Table 1**  
Study sample characteristics (N = 18,332).

|                                                | Frequency (n) | Percentage (%) |
|------------------------------------------------|---------------|----------------|
| Age at Wave 5 survey (years)                   |               |                |
| 36–54                                          | 4615          | 25.2           |
| 55–69                                          | 9418          | 51.4           |
| ≥ 70                                           | 4299          | 23.4           |
| Sex                                            |               |                |
| Male                                           | 11,501        | 62.7           |
| Female                                         | 6831          | 37.3           |
| Race/ethnicity                                 |               |                |
| Non-Hispanic White                             | 13,971        | 76.2           |
| Non-Hispanic Black                             | 1387          | 7.6            |
| Hispanic (any race)                            | 1721          | 9.4            |
| Non-Hispanic Other <sup>1</sup>                | 1253          | 6.8            |
| Rescue/recovery worker                         |               |                |
| Yes                                            | 8797          | 48.0           |
| No                                             | 9535          | 52.0           |
| 9/11 exposure <sup>2</sup>                     |               |                |
| Low/none                                       | 10,094        | 55.0           |
| Moderate                                       | 5642          | 30.8           |
| High                                           | 2596          | 14.2           |
| Ever 9/11-related PTSD symptoms <sup>*,3</sup> |               |                |
| Yes                                            | 3897          | 23.2           |
| No                                             | 12,911        | 76.8           |
| Ever lack of social support <sup>*,4</sup>     |               |                |
| Yes                                            | 6448          | 35.9           |
| No                                             | 11,514        | 64.1           |

**Note:** PTSD = post-traumatic stress disorder

<sup>\*</sup>Due to missing values, sum of frequencies do not equal the number of participants in the study sample.

<sup>1</sup> Non-Hispanic Other includes Asian, Pacific Islander, American Indian, Alaskan Native, Multi-racial, and unknown race.

<sup>2</sup> 0–2 9/11-related exposures were considered low/none, 3–4 were considered moderate, and ≥ 5 were considered high.

<sup>3</sup> Assessed with PTSD Checklist based on DSM-V criteria; any score of 33 or above out of 80 in any of the four follow-up surveys (Wave 2–Wave 5) was considered ever 9/11-related PTSD symptoms.

<sup>4</sup> Assessed with Modified MOS Social Support Survey (MSSS); any score less than 55 out of 100 in any of the latest 3 follow-up surveys (Wave 3–Wave 5) was considered ever lack of social support.

**Table 2**

Heavy and binge drinking status in Waves 2–5 among World Trade Center Health Registry enrollees (N = 18,332).

|                              | Wave 2        | Wave 3        | Wave 4        | Wave 5        | Ever <sup>1</sup> |
|------------------------------|---------------|---------------|---------------|---------------|-------------------|
| <b>Binge drinking status</b> |               |               |               |               |                   |
| Yes                          | 4848 (26.4)   | 5251 (28.6)   | 4350 (23.7)   | 3190 (17.4)   | 7735 (42.2)       |
| No                           | 13,484 (73.6) | 13,081 (71.4) | 13,982 (76.3) | 15,142 (82.6) | 10,597 (57.8)     |
| <b>Heavy drinking status</b> |               |               |               |               |                   |
| Yes                          | 2507 (13.7)   | 2475 (13.5)   | 2017 (11.0)   | 1905 (10.4)   | 4412 (24.1)       |
| No                           | 15,825 (86.3) | 15,857 (86.5) | 16,315 (89.0) | 16,427 (89.6) | 13,920 (75.9)     |

<sup>1</sup> Ever binge or heavy drinking in at least one survey wave from Waves 2–5.

drinking behavior among enrollees over the study period (Fig. 1). For binge drinking, the groups were very-low-stable (72.5 %), moderate-increasing (6.9 %), high-decreasing (11.8 %), and very-high-decreasing (8.8 %); for heavy drinking, the groups were very-low-stable (82.9 %), low-increasing (6.0 %), high-decreasing (5.9 %), and high-increasing (5.1 %). The high-decreasing and moderate-increasing groups in the binge drinking trajectory, high-increasing and high-decreasing groups in the heavy drinking trajectory, and very-low-stable and low-increasing groups in the heavy drinking trajectory were all found to have similar intercepts; however, they diverged significantly over time. Additionally, both plots showed cross-over and convergence among different groups.

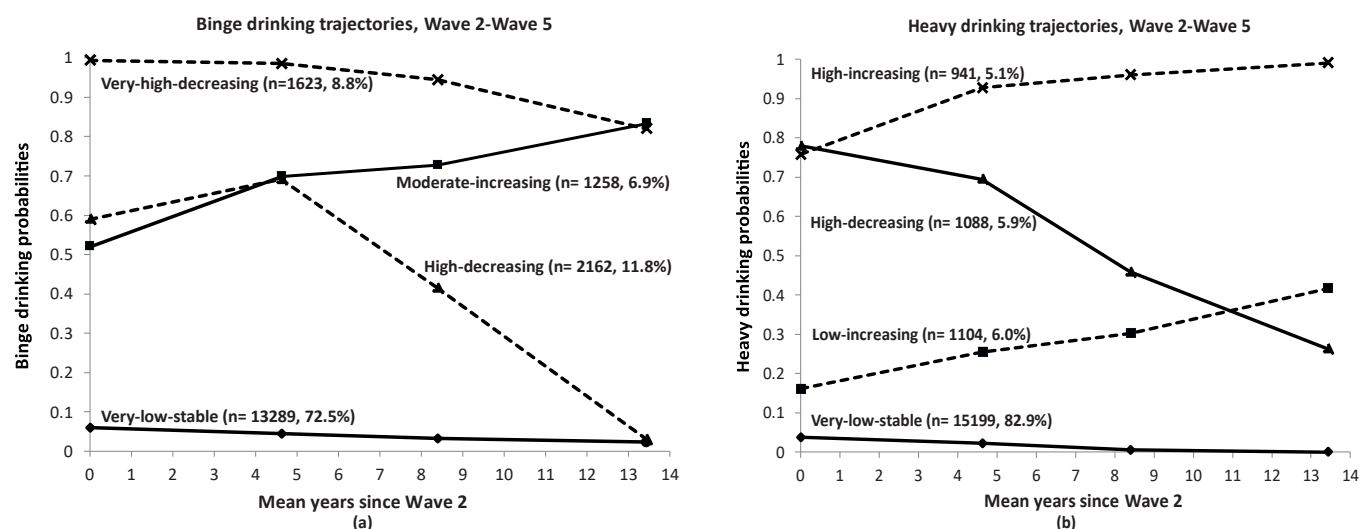
Multinomial regression analysis models assessing predictors of binge drinking trajectory group membership (Table 3) showed that, in comparison to the very-low-stable group, the odds of membership in the other three groups were significantly higher among enrollees who were male, non-Hispanic White, ever had 9/11-related PTSD, and had a high level of 9/11-related exposure. RRW had a higher likelihood of being in the moderate-increasing group (odds ratio (OR):1.21, 95 % confidence intervals (CI):1.06–1.38), whereas enrollees with low social support had a higher likelihood of being in the high-decreasing group (OR:1.14, 95 % CI:1.02–1.27) than the very-low-stable group. Similarly, in the heavy drinking model, when compared to the very-low-stable group, the odds of being in the other three groups were higher among enrollees who were non-Hispanic White, and who ever had 9/11-related PTSD. The odds of membership in the high-decreasing and high-increasing groups were significantly higher among enrollees with high 9/11-related exposures and low social support. Contrary to the binge drinking trajectory, female enrollees had higher odds of being in the low-increasing (OR:1.24, 95 % CI:1.08–1.42) and high-increasing (OR:1.53, 95 % CI:1.32–1.77) heavy drinking groups than males. Compared to adults aged 70 +, younger enrollees had higher

probability of being in all other binge and heavy drinking trajectory groups, with higher odds ratios observed among those aged 36–54 than among those aged 55–69 (e.g., OR for very high-decreasing binge drinking for 36–54 = 7.32; 95 % CI: 5.99–8.94; OR for 55–64 = 3.53, 95 % CI: 2.91, 4.28).

Dual trajectory modeling linked conditional probabilities of membership between heavy and binge drinking trajectory groups. The joint trajectory model for binge drinking (Fig. 2) showed the same four groups with similar distributions as the individual trajectory model; however, the joint trajectory model for heavy drinking was grouped as very-low-stable (76.0 %), low-increasing (5.5 %), moderate-decreasing (11.7 %), and high-decreasing (6.8 %). In the ranking order table (Table 4), both joint trajectory models were compared pairwise, with the very-low-stable groups for both drinking behaviors nearly completely clustered together (98.7 %). Around one third of the moderate-increasing (35.4 %) and the high-decreasing (38.2 %) binge drinking group belonged to the very-low-stable heavy drinking group, while the majority of the remaining individuals fell into the low-increasing (60.0 %) and moderate-decreasing (58.8 %) heavy drinking groups, respectively.

### 3.1. Post-hoc analysis

Table 5 presents a comparison of baseline (Wave 2) drinking behaviors, sociodemographic characteristics, and key covariates between the full Wave 1 cohort (N = 71,423), the analytic study sample (N = 18,332), and enrollees excluded due to missing responses on binge and/or heavy drinking questionnaires (n = 4562). Compared to the study sample, excluded enrollees were more likely to be female (41.6 % vs. 37.3 %), non-White (32.4 % vs. 23.8 %), and to have 9/11-related PTSD symptoms at Wave 1 survey (11.0 % vs. 9.1 %) and low social support (44.9 % vs. 35.9 %). The estimated percentage of each trajectory group membership, AVPs, and odds of correct classification (OCC)



**Fig. 1.** Individual trajectories of a) binge drinking and b) heavy drinking among World Trade Center Health Registry enrollees across Wave 2-Wave 5, 2006–2021 (N = 18,332)<sup>1</sup> Each point reflects model-estimated posterior probabilities of group membership across waves, generated using PROC TRAJ.

**Table 3**

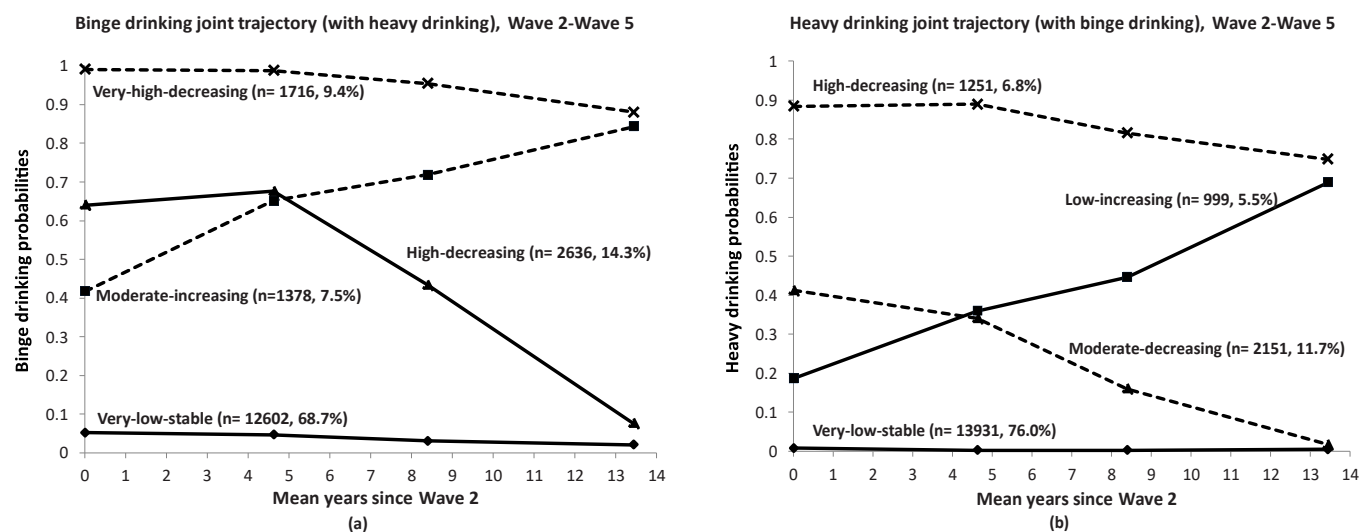
Adjusted OR's and 95 % CI's for associations between sociodemographic factors, 9/11 exposure and social support, and binge and heavy drinking trajectory group membership<sup>1,2</sup> (N = 18,332).

|                                        | Binge Drinking      |                   |                      | Heavy Drinking    |                   |                   |
|----------------------------------------|---------------------|-------------------|----------------------|-------------------|-------------------|-------------------|
|                                        | Moderate-increasing | High-decreasing   | Very-high-decreasing | Low-increasing    | High-decreasing   | High-increasing   |
|                                        | OR (95 % CI)        | OR (95 % CI)      | OR (95 % CI)         | OR (95 % CI)      | OR (95 % CI)      | OR (95 % CI)      |
| <b>Age at Wave 5 survey (years)</b>    |                     |                   |                      |                   |                   |                   |
| 36–54                                  | 5.47 (4.47,6.69)    | 3.57 (3.08,4.14)  | 7.32 (5.99,8.94)     | 2.56 (2.11,3.11)  | 1.55 (1.28,1.88)  | 1.98 (1.61,2.42)  |
| 55–69                                  | 2.61 (2.15,3.18)    | 2.04 (1.78,2.34)  | 3.53 (2.91,4.28)     | 1.77 (1.48,2.13)  | 1.44 (1.21,1.71)  | 1.59 (1.32, 1.92) |
| ≥ 70                                   | ref                 | ref               | ref                  | ref               | ref               | ref               |
| <b>Sex</b>                             |                     |                   |                      |                   |                   |                   |
| Male                                   | ref                 | ref               | ref                  | ref               | ref               | ref               |
| Female                                 | 0.81 (0.71,0.93)    | 0.45 (0.40,0.51)  | 0.34 (0.29,0.39)     | 1.24 (1.08, 1.42) | 0.93 (0.81,1.08)  | 1.53 (1.32,1.77)  |
| <b>Race/ethnicity</b>                  |                     |                   |                      |                   |                   |                   |
| NH White                               | ref                 | ref               | ref                  | ref               | ref               | ref               |
| NH Black                               | 0.49 (0.37,0.65)    | 0.51 (0.41,0.64)  | 0.39 (0.29,0.53)     | 0.53 (0.40,0.70)  | 0.40 (0.29,0.55)  | 0.34 (0.24,0.48)  |
| Hispanic (any race)                    | 0.82 (0.68,1.00)    | 0.79 (0.67,0.93)  | 0.55 (0.45,0.68)     | 0.83 (0.67,1.02)  | 0.63 (0.50,0.79)  | 0.49 (0.38,0.64)  |
| NH Other                               | 0.51 (0.39,0.68)    | 0.56 (0.46,0.70)  | 0.31 (0.23,0.43)     | 0.56 (0.42,0.74)  | 0.40 (0.29,0.56)  | 0.33 (0.23,0.48)  |
| <b>Rescue/recovery worker</b>          |                     |                   |                      |                   |                   |                   |
| Yes                                    | 1.21 (1.06,1.38)    | 1.05 (0.95, 1.16) | 1.15 (1.02,1.29)     | 0.97 (0.85,1.11)  | 1.07 (0.93, 1.23) | 0.98 (0.85, 1.14) |
| No                                     | ref                 | ref               | ref                  | ref               | ref               | ref               |
| <b>9/11 exposure</b>                   |                     |                   |                      |                   |                   |                   |
| Low/none                               | ref                 | ref               | ref                  | ref               | ref               | ref               |
| Moderate                               | 0.98 (0.85,1.13)    | 1.35 (1.21,1.51)  | 1.43 (1.26,1.61)     | 1.07 (0.93,1.23)  | 1.30 (1.13,1.50)  | 1.12 (0.96,1.31)  |
| High                                   | 1.31 (1.10,1.55)    | 1.49 (1.30,1.71)  | 1.45 (1.24,1.70)     | 1.09 (0.90,1.31)  | 1.40 (1.17,1.68)  | 1.25 (1.03,1.52)  |
| <b>Ever 9/11-related PTSD symptoms</b> |                     |                   |                      |                   |                   |                   |
| Yes                                    | 1.32 (1.14,1.54)    | 1.46 (1.30,1.65)  | 1.28 (1.11,1.48)     | 1.22 (1.04, 1.43) | 1.79 (1.54,2.08)  | 1.37 (1.16,1.62)  |
| No                                     | ref                 | ref               | ref                  | ref               | ref               | ref               |
| <b>Ever lack of social support</b>     |                     |                   |                      |                   |                   |                   |
| Yes                                    | 1.00 (0.88,1.15)    | 1.14 (1.02,1.27)  | 1.09 (0.97, 1.23)    | 1.14 (1.00, 1.31) | 1.20 (1.04,1.37)  | 1.18 (1.02,1.36)  |
| No                                     | ref                 | Ref               | ref                  | ref               | ref               | ref               |

**Note:** OR=Odds ratio; CI=Confidence interval; NH=Non-Hispanic; PTSD=post-traumatic stress disorder. Bolded results are statistically significant.

<sup>1</sup> Comparison of the three binge and heavy drinking groups was performed using the very-low-stable group as a reference

<sup>2</sup> Multiple imputations have been performed for all the missing values in the covariates before performing multinomial regression analyses.



**Fig. 2.** Dual/Joint trajectories of a) binge drinking (with heavy drinking) and b) heavy drinking (with binge drinking) among World Trade Center Health Registry enrollees across Wave 2-Wave 5, 2006–2021 (N = 18,332)<sup>1</sup> Each point reflects model-estimated posterior probabilities of group membership across waves, generated using PROC TRAJ.

were then addressed for the individual and joint trajectory models (Tables 6 & 7). The AVP's were ≥ 70 % across trajectory subgroups, indicating adequate classification (Nagin, 2005; Nagin et al., 2018), and higher OCC values nearly always supported our analytic approach's appropriateness.

Lastly, because disparate patterns of odds among binge and heavy drinking trajectory groups' regression results between men and women

were observed, further trajectory analyses were conducted stratified by sex (Figure 3 & Table 8). AVPs were ≥ 70 % nearly in all cases. Though females were more likely than males to be in the very-low-stable binge-drinking group (79.9 % vs. 67.2 %), they were less likely to be in the very-low-stable heavy-drinking group (79.5 % vs. 83.0 %). Furthermore, females had initially higher or increasing patterns for heavy drinking compared to males who typically had more decreasing

**Table 4**

Rank-ordering probability of heavy drinking trajectory groups against binge drinking trajectory groups among World Trade Center Health Registry enrollees, 2006–2021 (N = 18,332).

| Binge drinking |      |                                 |                                 |                                 |                                  |
|----------------|------|---------------------------------|---------------------------------|---------------------------------|----------------------------------|
| Heavy drinking | Rank | Very-low-stable                 | Moderate-increasing             | High-decreasing                 | Very-high-decreasing             |
|                | 1    | Very-low-stable<br>(98.7 %)     | Low-increasing<br>(60.0 %)      | Moderate-decreasing<br>(58.8 %) | High-decreasing<br>(62.2 %)      |
|                | 2    | Low-increasing<br>(0.8 %)*      | Very-low-stable<br>(35.4 %)*    | Very-low-stable<br>(38.2 %)*    | Moderate-decreasing<br>(33.9 %)* |
|                | 3    | Moderate-decreasing<br>(0.1 %)* | High-decreasing<br>(4.4 %)*     | High-decreasing<br>(2.8 %)*     | Low-increasing<br>(3.9 %)*       |
|                | 4    | High-decreasing<br>(0.4 %)*     | Moderate-decreasing<br>(0.2 %)* | Low-increasing<br>(0.3 %)*      | Very-low-stable<br>(<0.1 %)*     |

\* Significant difference ( $P < 0.05$ ) from the Rank 1 group; statistical significance was determined based on least square means test of difference in proportions (using generalized linear modeling test).

\* Figures and [supplementary tables](#) (Table 5–9) are provided as two separate documents.

patterns.

Additional trajectory analyses stratified by age revealed distinct patterns in both binge and heavy drinking (Figure 4 and Table 9). High-risk binge drinking trajectories (high-decreasing or very high-increasing) were most prevalent among adults aged 36–54 (42.3 %), compared with 25.7 % in ages 55–69 and 11.9 % in ages 70 + . Similarly, increasing heavy drinking (moderate- or high-increasing) was observed in 21.3 % of adults aged 36–54, versus 13.1 % in ages 55–69 and only 3.1 % in ages 70 + . In contrast, very low-stable binge trajectories were most common among older adults (77.5 % in ages 70 + , 60.3 % in ages 55–69, and 54.3 % in ages 36–54), with a similar pattern for heavy drinking (88.4 %, 82.3 %, and 75.5 %, respectively). Most groups had AVPs  $\geq 70$  %.

#### 4. Discussion

Numerous studies have identified both binge and heavy drinking trajectories across different population ages, especially among those entering adulthood (Berg et al., 2013; Ranker et al., 2023); however, to our knowledge, this is the first study to report distinct, heterogeneous binge and heavy drinking trajectories over an extended period of time across all aged adults in a longitudinal study population exposed to a disaster. Furthermore, we investigated contemporaneous heavy and binge drinking in a 9/11-survivor cohort, ushering an additional dimension into our study. In addition to groups who didn't drink or drank infrequently for both binge and heavy drinking, we described several patterns where early high drinking behavior diminished over time and patterns where low/moderate drinking increased over time.

Our study population had higher prevalence of binge drinking (17.4 %) and heavy drinking (10.4 %) in Wave 5 compared to national estimates (12.3 % and 6.8 %, respectively) from the 2021 Behavioral Risk Factor Surveillance System (BRFSS) survey (BRFSS Survey Data and Documentation, 2021). Some of the groups in our binge and heavy drinking models were similar to other studies. For example, with respect to binge drinking, the very-low-stable, moderate-increasing, and very-high-decreasing trajectory groups were comparable to the no/infrequent, late-escalating, and chronic groups, respectively, from studies examining trends in alcohol intake among longitudinal cohorts of younger populations (Fairman et al., 2019; Ranker et al., 2023). Each of our heavy drinking trajectory patterns closely matched the steady-low, increasing, decreasing, and steady-high patterns in a different study among a mid-adult population (Berg et al., 2013). Despite these similarities, these studies found five to six distinct binge and heavy drinking trajectories, compared to our four-group models (Fairman et al., 2019; McDevitt-Murphy et al., 2015; Ranker et al., 2023). This is likely because these studies focused on young to mid-adulthood populations, whereas our study sample ranged from ages 23–90 at the time when the first alcohol-related questions were administered. Moreover, our study was conducted among persons who were all exposed to a large-scale

traumatic event. This shared exposure to 9/11 may have contributed to more homogeneous or decreasing drinking trajectories over time, although patterns before and immediately after the disaster were not captured.

Based on our regression results, enrollees with a history of PTSD were less likely to be in the very-low-stable groups for binge and heavy drinking, similar to numerous studies where high levels of binge and heavy drinking were common among those with PTSD (Boscarino et al., 2011; McDevitt-Murphy et al., 2015; Welch et al., 2014, 2017). Non-Hispanic Whites were also more prone to drink both binge and heavily when compared to other races/ethnicities, which is consistent with 2018 U.S. estimates where non-Hispanic White adults were 2–3 times more likely to binge and heavy drink than other races/ethnicities (Boersma et al., 2020; Bohm et al., 2021). High binge drinking behavior groups were linked to a higher number of 9/11-related exposures, consistent with previous findings among the Registry population, indicating a strong association between binge drinking and 9/11 exposures (Welch et al., 2017). The same study found that individuals < 65 years old were more likely to binge drink; in this study, those aged 36–64 had a higher likelihood of being in a binge trajectory group other than very-low-stable compared to those aged  $\geq 65$  (Welch et al., 2017). Similar findings were found for heavy drinking, which is consistent with data from the U.S. National Health Interview Survey (NHIS) (Boersma et al., 2020).

The joint trajectory analysis revealed similar relationships between binge and heavy drinking, as the majority of participants in each binge drinking trajectory group exhibited similar patterns of heavy drinking. For example, almost all (98.7 %) of those in the very-low-stable binge drinking group were also in the very-low-stable heavy drinking group. However, more than one-third of participants in the moderate-increasing and high-decreasing binge drinking groups belonged to the very-low-stable heavy drinking group, suggesting that while patterns of binge drinking may have changed over time, heavy drinking remained constant. Although the same number of groups emerged from both individual and joint models, the dual trajectory approach better captures the co-development of binge and heavy drinking over time and reflects their interdependence (Nagin et al., 2024).

Previous research indicated that males were more likely to engage in excessive alcohol consumption among 9/11-exposed enrollees than females (Welch et al., 2014, 2017). Consistent with this, we found that females were more likely to be in the very-low-stable binge drinking group than males. Conversely, females were more likely than males to be in one of the increasing heavy drinking groups. Notably, despite these sex-specific differences, most participants in our cohort were classified into low-risk drinking trajectories, reflecting overall stability in drinking patterns over time. Our findings reflect a recent study among NHIS participants which reported females, who drank less frequently than males one to two decades ago, are gradually closing the gap in alcohol consumption prevalence while, males have fairly stable consumption

trends (White, 2020).

One important methodological consideration in our trajectory modeling is the choice of time scale. In our primary analyses, we used a cohort time scale, anchoring trajectories from a calendar time point (Wave 2 interview) up to Wave 5 interview for all participants, to examine changes in drinking behavior in response to 9/11. While this approach is well-suited for studying changes after a mass-trauma event, it introduces complexity in interpreting developmental effects, as participants were at different ages at baseline (Leggat et al., 2022; Nagin, 2005). To address this, age-stratified trajectory analysis revealed distinct drinking patterns, with older adults (70+) predominantly following very low binge and heavy drinking patterns, consistent with prior research showing reduced alcohol use with aging (Moore et al., 2005). In contrast, midlife adults (36–54) exhibited greater heterogeneity, with over 40% in high-risk binge drinking groups and more than 20% in increasing heavy drinking trajectories, suggesting midlife as a critical period for sustained or escalating use (Andreacchi et al., 2024). Adults aged 55–69 showed intermediate patterns, with a minority exhibiting persistent heavy use.

The most prominent limitations of our study are the use of self-reported data and the loss of follow-up data between survey waves. Self-reported alcohol consumption may not accurately reflect actual intake, leading to the underestimation of the drinking frequency and severity. Furthermore, our study only considered self-reported alcohol consumption and did not have information available on behaviors consistent with or diagnosis of AUD. Additionally, participants were assigned to trajectory groups based on their maximum posterior probability, and this group membership was treated as fixed in the regression models. While this is a common analytic strategy, it does not account for uncertainty in group assignment and may introduce bias in the estimated associations (Nagin, 2014; Nagin et al., 2018). We also relied on complete-case analysis for alcohol outcomes, which may lead to some selection bias. Predictors such as 9/11-related PTSD and lack of social support were also collected from self-administered questionnaires rather than clinical review; however, the assessment of such predictors used widely accepted tools (PCL and MSSS-5) with adequate diagnostic efficiency (Blanchard et al., 1996; Dao-Tran et al., 2023). Data used for the 9/11-exposure summary were collected 3–4 and 5–6 years after 9/11 (Waves 1 and 2, respectively) and are therefore subjected to recall bias. Another limitation is no data availability on drinking behavior pre-9/11/2001 and in the immediate years after 9/11 prior to Wave 2. Moreover, co-use of other substances (e.g., tobacco, drugs) was not measured, and the study did not account for sociodemographic variables like household income and employment status, which have been linked to binge and heavy drinking, due to significant missing data; using the available data would have reduced our sample size and the statistical power of our findings. Additionally, our models adjusted for both 9/11 exposure and PTSD, but since PTSD may lie on the causal pathway, this could represent over-adjustment and potentially weaken true associations. Future studies may explore alternative approaches to better address these relationships. Finally, while Wave 5 overlapped with the COVID-19 pandemic, we were unable to account for pandemic-related influences due to limited data coverage. Future waves of data collection may offer an opportunity to assess how COVID-19 shaped longer-term drinking trajectories in this population. In contrast, strengths of the study include its large sample size, exploration of drinking behaviors across an extended period, and contribution to the excessive alcohol drinking behavior literature by revealing patterns of both binge and heavy drinking behaviors among a disaster-affected population of all adult ages.

## 5. Conclusion

Though most enrollees have very low to no drinking trends, their exclusion from further follow-up may result in subtle drinking behaviors going undetected in the early stages. Individuals with increasing,

decreasing, or chronically high binge or heavy drinking trends deserve further investigation from a public health standpoint, as they are critical for addressing AUD, a painful disease from individual, family, and societal perspective. Our findings highlight the importance of longitudinal population-based studies in comprehending the distinct binge and heavy drinking patterns based on age strata, and sexual differences (male vs female) and provide critical insights for clinicians when developing preventive strategies and raising awareness. Future research can explore the correlation between individuals' excessive-drinking habits and their physical and mental health.

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## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.drugalcdep.2025.112912.

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