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Self-Reported Traumatic Brain Injury and Its Biopsychosocial Risk Factors in Siblings of Individuals with Neurodevelopmental Conditions

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ABSTRACT

Siblings of individuals with neurodevelopmental conditions (NDCs) are situated within a complex system of risk and resilience factors for poor outcomes, many of which overlap with the risk of traumatic brain injury (TBI) and correlate with poorer recovery trajectories. This study used Bayesian analyses to characterize and compare TBI and biopsychosocial risk factors among 632 siblings (207 NDC, 425 controls; mean age 20.54 years, range 10–30, 78.48% female). NDC siblings had a higher self-reported lifetime history of TBI compared to controls (14.98% versus 6.35%), with most reporting more than one TBI, and at an earlier age. TBI history was associated with psychiatric diagnoses and subclinical NDC features. Family and structural factors related to TBI included poorer parent-child relationship, NDC diagnoses of autism or fetal alcohol spectrum disorder, minority ethnicity, and lower income. Findings have implications for health literacy, TBI education and screening, and implementation of family support.

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Traumatic brain injury epidemiology and risk factors

Traumatic brain injury (TBI) is a form of acquired brain injury involving a disruption in the normal function of the brain caused by direct or indirect impact to the head (CDC Centers for Disease Control and Prevention, 2017) Symptoms following TBI vary by severity of injury, and interact with psychosocial, clinical, treatment-related, and biological mechanisms and structural determinants of health. This complexity may underlie the difficulty with accurate prognostication and understanding of essential factors to optimize treatment and recovery (Bagg et al., 2024). TBI has become a global health priority and is associated with significant individual and societal burden. In 2019, there were an estimated 27.16 million new TBI cases of any severity, and 48.99 million prevalent cases worldwide (Guan et al., 2023). Up to one in five adolescents have a history of TBI, which is associated with compromised long-term functional outcomes (Ilie et al., 2020). These figures are likely an underestimate due to continued underreporting and poor understanding of mild TBI (mTBI) in particular (Daugherty et al., 2023; Silverberg et al., 2020), although it is well established that moderate-to-severe

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TBI poses a risk of permanently modifying neurodevelopmental trajectories (Babikian & Asarnow, 2009). Efficient and precise treatment of TBI in youth is thus one of the largest unmet global public health needs (Podolak et al., 2021).

Symptoms and traits prevalent in neurodevelopmental conditions (NDCs) are associated with an increased risk of mild to severe TBI, including impulsivity, attention problems, social cognitive deficits, poor executive functioning, and emotional and behavioral dysregulation (Howlett et al., 2022; Wood & Worthington, 2017). Some studies report positive wellbeing outcomes for these siblings, such as resilience and personal growth (Leedham et al., 2020). Despite some positive findings, there is robust evidence indicating a high prevalence of physical and mental health disorders among these siblings (Wang et al., 2022). While there are known associations between NDC diagnoses and mTBI, particularly Attention-Deficit Hyperactivity Disorder (ADHD; Brunkhorst-Kanaan et al., 2021), autism (Cook et al., 2023), and Fetal Alcohol Spectrum Disorder (FASD (Tan et al., 2022), risk of TBI in siblings of persons with NDCs has not previously been examined. Siblings of individuals with NDCs experience compromised psychosocial and cognitive functioning, attributable to a complex interaction of genetic and environmental vulnerabilities (Shivers et al., 2018; Wolff, Magiati, Roberts, Pellicano, et al., 2022). NDC siblings self-report strikingly high rates of psychiatric diagnoses (Wolff et al., 2023), four times the rate of suicidal thoughts and behaviors (Wolff et al., 2023b), objectively poorer executive functioning (Wolff et al., 2023a), and high levels of subclinical NDC traits (Wolff et al., 2023) compared to siblings of persons without NDCs. There is also evidence that siblings of persons with FASD and autism have greater psychosocial and behavioral difficulties than other NDC siblings (Marquis et al., 2020; Wolff et al., 2023b).

TBI severity is associated with greater ADHD symptoms (Asarnow et al., 2021), and ADHD onset tends to antedate the first TBI (Biederman et al., 2015). This indicates that factors other than trauma-related altered brain function complicate risk, and there may be a genetic propensity toward TBI (Asarnow et al., 2021). Similarly, autistic individuals have higher rates of any TBI, yet non-autistic siblings also experience elevated rates compared to the general population, implicating a risk independent of an autism diagnosis itself, perhaps attributable to underlying environmental and genetic vulnerability (Khachadourian et al., 2023). Further, genetic predispositions to certain risk traits and psychiatric diagnoses correlate with risk of TBI, pathophysiology of injury, neuroplasticity, and individual differences in psychosocial and cognitive functioning (Ilie et al., 2020). For instance, alexithymia is associated with TBI (Fynn et al., 2021) and both autistic traits (Kinnaird et al., 2019) and ADHD symptoms (i.e., impulsivity and hyperactivity; Donfrancesco et al., 2013).

From a biopsychosocial perspective, there are structural variables contributing to risk for, and outcomes following, TBI (Dams O'Connor et al., 2023), with interactive effects between biological (i.e., sex, ethnicity, cognition), psychological (i.e., depression, self-efficacy, coping styles), and social/structural (i.e., employment, education, income, social support) risk modifiers (Mamman et al., 2023). The same psychosocial stressors are known to negatively impact NDC sibling functioning and long-term outcomes (Kovshoff et al., 2017; Wolff, Magiati, Roberts, Pellicano, et al., 2022). For instance, we have previously found that parent-child communication and relationship quality are poorer in NDC siblings than controls (Wolff et al., 2023), and there are known bidirectional negative relations between family cohesion and communication with risk and recovery from TBI (Fischer et al., 2022).

Outcomes following traumatic brain injury

Psychological, neurocognitive, physical, and/or behavioral sequelae are experienced by up to one-third of individuals with mTBI (Chadwick et al., 2022; Ledoux et al., 2019). Cognitive, affective, and behavioral consequences of TBI across the severity spectrum are often more disabling than physical sequelae, including personality changes, suicidality, novel psychiatric diagnoses, and post-traumatic stress (Howlett et al., 2022; Lennon et al., 2023), with any severity TBI history in psychiatric and mental health services estimated at 17–58% (Davies et al., 2023). Individuals with TBI, including mild

cases, experience elevated internalizing (withdrawal, anxiety, depression) and externalizing (conduct problems, aggression, hyperactivity) difficulties over time (Gornall et al., 2021; Stewart et al., 2022), high levels of psychiatric hospitalization and self-harm (Ledoux et al., 2022), and are three times more likely to attempt suicide than youth without a history of TBI (Ilie et al., 2014). Further, TBI is a risk factor for later offending behavior (Kennedy et al., 2017), including exhibiting bidirectional associations with conduct problems (Carr et al., 2023) and co-occurring substance use (Olsen & Corrigan, 2022).

There are also physical comorbidities, lower adaptive functioning, and cognitive and learning difficulties associated with TBI in youth, with a slowing or shifting in development resulting in adolescents "growing into their deficits" (Serpa et al., 2021). School performance can be impacted in mild to severe TBI due to medical absences, psychological difficulties, and cognitive limitations including sleep disturbance, fatigue and inattention (DeMatteo et al., 2022; Luther et al., 2020). Additionally, youth with TBI experience discrimination, bullying, social isolation, and school avoidance (Lindsay et al., 2023). Premorbid yet previously undiagnosed mental health or cognitive inefficiencies are present in NDC siblings (Wolff et al., 2023a) which may also emerge following TBI when cognitive capacities are exceeded by demands of everyday functioning, compounded by socioemotional, physiological, and family reactions to injury (Babikian, 2023). Mental health, cognitive and behavioral difficulties thus appear to be the rule rather than the exception in TBI (Schachar et al., 2015).

Other research points to the impact of social determinants of health impacting sibling wellbeing, including income, education, and ethnicity (Marquis et al., 2019), which similarly predict risk for, and outcomes following, TBI of any severity (Johnson & Diaz, 2023). For example, younger age of injury and developmental stage at the time of TBI) are important prognostic factors for poorer outcomes (Neumane et al., 2021; Ryan et al., 2014). Less conclusively, male sex is a risk factor for sustaining TBI (Frost et al., 2013), while female sex is a predictor of poorer long-term functional outcomes in moderate-to-severe TBI (Breeding et al., 2024). There is a similar differential susceptibility to poorer outcomes among NDC siblings based on age and sex (Marquis et al., 2020; Wolff, Magiati, Roberts, Pellicano, et al., 2022). As such, examining demographic variables among NDC siblings with TBI may provide important insights into subgroups of vulnerable siblings and possible preventative measures.

Rationale for the present study

There are complex, dimensional, and overlapping features involving systemic interpersonal relations (e.g., family communication and problem-solving) and factors external to the family which impact child neurobehavioral outcomes in TBI (Fischer et al., 2022; Taylor et al., 2001). Research to date has not examined these factors and frequency of TBI in NDC siblings. This is a striking gap in the literature, given NDC siblings experience higher levels of risk factors for TBI, such as emotional and behavioral dysregulation, executive dysfunction, subclinical autistic and ADHD traits, and family-level disruptions (Wolff et al., 2023). Characterising TBI and associated risk factors within a bioecological framework (Bronfenbrenner, 1995) in NDC siblings is an important first step in formulating prevention and management strategies for evidence-based, individualized, TBI recovery.

Study aims and hypotheses

The present study had two aims and two corresponding hypotheses. First, we aimed to examine and compare the prevalence and characteristics of self-reported TBI among siblings of persons with and without NDCs. It was hypothesized that siblings of persons with NDCs would have higher rates of TBI at younger ages and of greater severity than controls (i.e., siblings of persons without NDCs), due to both higher levels of risk factors and possible genetic propensity to TBI via elevated NDC traits.

Second, we aimed to explore the cross-sectional associations within the full sample between self-reported TBI and psychosocial factors, including subclinical NDC traits, mental health diagnoses, and

demographic risk variables and social determinants of health. We hypothesized that TBI would be associated with more NDC traits, higher prevalence of mental health diagnoses, and risk demographics (i.e., male sex, minority ethnicity, lower income).

Methods

This research was funded by an Australian National Health and Medical Research Council (NHMRC) grant (1184770) and ethical approval was granted by the Human Ethics Office at The University of Western Australia (2020/ET000049). This study was pre-registered: https://osf.io/8wytd.

Participants and procedure

The survey was co-designed and piloted with a Sibling Advisory Group of eight NDC siblings (mean age 16.7 years, age range 9–28 years, 50% male, two accompanied by their mothers), consulted in focus group format on four occasions via Zoom, prior to survey distribution. Subsequent recruitment of the survey's participants occurred through the authors' Institute and University e-mail and social media, community and student recruitment pools, and the recruitment service Qualtrics Panels, to optimize diversity of the sample. Participants had to be older than eight years, not have a diagnosis of an NDC themselves, and have at least one sibling. An online survey was then released via snowball and convenience sampling to NDC siblings and controls (i.e., individuals with siblings without NDCs) as part of a larger study investigating the wellbeing and functional outcomes of siblings. The survey included a range of standardized and custom self-report questionnaires measuring selected risk and resilience factors, and a selection of these were focused on in the present study based on the above hypotheses (see Measures below). Participants could choose to enter a monthly $100 prize draw after completing the survey. The online survey was self-administered remotely via the online survey platform Qualtrics, open globally between May 2021 and September 2021.

Measures

Structural validity, reliability, and sum scores

All scales and subscales were tested for their structural validity using confirmatory factor analysis (Thompson, 2004), using the mean- and variance-adjusted weighted least squares method (WLSMV; DiStefano & Morgan, 2014). Composite reliability (standardized alpha; CR; Peterson & Kim, 2013) assessed the measures' internal consistency.

Mental health diagnoses

Siblings self-reported the presence or absence of categorical psychiatric diagnoses, in response to the question, "have you ever received a diagnosis of any of the following?" followed by a checklist of all DSM-5 psychiatric diagnoses (e.g., depression, anxiety, eating disorders, psychotic disorders) and "other" option. Responses were then coded as 1 (at least one diagnosis) or 0 (no diagnoses). Type of psychiatric diagnosis has been reported on previously (Wolff et al., 2023) and was not the focus of the present study.

ADHD symptoms (youth externalizing behavior screener, YEBS; Arslan, 2019)

The YEBS 12-item self-report measure is composed of three subscales: conduct problems (CP, e.g., "I don't follow rules, I often break them"), hyperactivity (HA; e.g., "I am an overactive person; I can't help moving"), and attention problems (AP, e.g., "I get distracted easily; I have difficulty concentrating"). Items are scored on a 4-point Likert scale from 1 (almost never) to 4 (almost always), with higher scores representing more difficulties. The scale has good reliability and construct validity in samples of children and adolescents (Arslan, 2019). CR in our sample was

0.82 (NDC) and 0.83 (control) for HA; 0.91 (NDC) and 0.94 (control) for AP; 0.85 (NDC) and 0.88 (control) for CP.

Autistic traits (autism quotient, AQ-10; Allison et al., 2012)

The AQ-10 is a 10-item measure designed to screen for autistic traits, with scores ranging 1–10 and higher scores indicating more autistic traits (Allison et al., 2012). The AQ-10 has high internal consistency and discriminative validity in autistic and non-autistic participants, and good validity measuring individual differences in autistic traits in population-based studies (Lundin et al., 2019). CR in our sample was 0.74 (NDC) and 0.82 (control).

Alexithymia (Perth alexithymia questionnaire, PAQ; Preece et al., 2018)

The PAQ is a 24-item self-report measure of alexithymia with five subscales: Negative-Difficulty identifying feelings (N-DIF), Positive-Difficulty identifying feelings (p-DIF), Negative-Difficulty describing feelings (N-DDF), Positive-Difficulty describing feelings (p-DDF); and General-Externally orientated thinking (G-EOT). Scored on a 5-point Likert scale from 1 (strongly disagree) to 5 (strongly agree), higher scores represent higher alexithymia. The PAQ has excellent psychometric properties (Preece et al., 2018). We used a 10-item short-form of the scale, with two items from each of the five subscales. CR in our sample was 0.91 (NDC) and 0.94 (control).

Parent-child relationship (Parent – adolescent communication scale, PACS; Barnes & Olson, 1985)

The PACS measures the quality of parent-child interactions and communication with reference to at least one parent/caregiver in the participants' life. It consists of ten items scored on a 5-point Likert scale from 1 (strongly disagree) to 5 (strongly agree), with higher scores indicating better parent-child communication quality. The PACS has good internal consistency and construct validity (Barnes & Olson, 1985). CR was 0.96 for both groups in our sample.

Traumatic brain injury

Siblings were asked to report on their history of TBI, including the number of TBIs, age of first injury, and time in months since the most recent TBI. They were asked to provide a Glasgow Coma Scale (GCS) score if known, loss of consciousness period if known, or otherwise estimate mild to severe classification, based on the definition provided: "The Glasgow Coma Scale score includes classifications for mild, moderate, and severe TBI, respectively, as follows: 13–15 (mild), 9–12 (moderate), or 3–8 (severe); post-traumatic amnesia or alteration of consciousness (<1 day, 1–7 days, >7 days), and loss of consciousness duration (<30 minutes, 30 minutes to 24 hours, >24 hours)." The GCS is widely accepted as the gold standard for assessing level of consciousness and the evaluation of the severity of TBI (Anestis et al., 2023). CR was 0.88 for the NDC group and 0.85 for the control group in our sample. As "mild TBI" or "concussion" are underreported due to ambiguous definitions and awareness, the following layperson, culturally appropriate definition was also provided (Alosco et al., 2017): "A concussion can happen when you have a blow to the head that caused you to have symptoms (like headache, dizziness, trouble sleeping, difficulty remembering or concentrating) for any amount of time, even if you did not black out. Whenever anyone gets a ding or their bell rung, that might also be a concussion."

Demographics

Siblings reported on environmental risk and resilience variables, including country of origin, ethnicity, socioeconomic status, NDC type, age, and sex. Participants were also asked to report on whether their sibling had a previous TBI.

Data analysis

Bayesian analysis was used, which is suited to quantifying the relative success of hypotheses at predicting the observed data (Kruschke, 2018), which is important given the heterogeneity in NDC sibling functional outcomes across studies (Wolff, Magiati, Roberts, Pellicano, et al., 2022). Standards for reporting Bayesian analyses were followed (Kruschke, 2021). All analyses used R software, version 4.3.2 (R Core Team, 2023), with packages JAGS (Plummer, 2013), jagsUI (Kellner, 2021), abtest (Gronau, 2019), and rstanarm (Goodrich et al., 2022). Data are available on OSF: https://osf.io/6w7ar/.

Power analysis

This study was part of the larger Sibling Project, which aimed to maximize recruitment and diversity. Power was reached for the baseline analysis (Wolff et al., 2023). Post-hoc power analyses for the present study employing sample size simulations used the BayesFactor package in R (Morey, 2023). Using Cohen's *d* guideline of 80% power, a study with 200 participants (100 per group) has power to exhibit a moderate effect, $d = 0.5$, at both $p = .05$ and 0.01, and a Bayes Factor of 3 as criterion values, with a Type II error rate of 0.06 (1–0.94 = 0.06).

Data preparation

The data extracted from Qualtrics initially consisted of 1486 respondents, as part of the larger Sibling Project. Pairwise deletion occurred for any participant completing <50% of the survey ($n = 325$) and with <5-minute completion times ($n = 323$), resulting in 838 siblings. Participants with >20% missing total data were removed ($n = 123$). We did not use multiple imputation for these 123 participants, as missing data included demographics, which prevented us from categorizing these siblings into NDC or control groups, in addition to scale-based missing data, which is not recommended to impute for >20% missing (Dong & Peng, 2013). This resulted in 715 participants (235 NDC, 480 controls; see Wolff et al., 2023). Correlations between the percentage of missing data per item indicated assumptions of missing at random were met (Little, 2021). No questions had forced responses, as per our Ethics approval. Only siblings choosing to respond to the questions regarding TBI were included in the present analysis, resulting in 632 participants (207 NDC, 425 controls; 88.39% of the full sample). Independent sample t-tests indicated absence of effect of group (i.e., full versus smaller sample) on demographics (i.e., parental education, ethnicity, sex, mean age, income) between the full sample and the present study.

Main analyses

To address Aim 1, descriptive statistics characterized the prevalence, severity, and age of injury of TBI among the full sample. Tests of non-normality were appropriate. Group comparisons between NDC and controls were evaluated with both Welch's *t*-tests and Bayesian independent sample *t*-tests using the normalized rank of the dependent variable (i.e., inverse-normal transformation), with a zero-centered Cauchy prior with width 0.707 for the standardized mean difference (effect size δ) and uniform prior for model probabilities (see Supplementary Table S1 for unstandardized mean differences). The relative risk with corresponding credible interval was obtained using the Bayesian A/B test with two uninformative (uniform) beta (1,1) priors.

For Aim 2, Bayesian bivariate Kendall's tau correlation (τ_b) coefficients were examined for all variables using an uninformative Wishart distribution and a beta-binomial (1,1) model selection prior. Multi-collinearity was not observed, and Bayesian methods provided robust estimation of regression parameters (Assaf & Tsionas, 2021).[1] We specified two-sided analyses.[2]

Inference criteria

Bayesian hypothesis testing was selected as it permits stronger conclusions regarding evidence of between-group equivalence, rather than lack of difference (Wagenmakers et al., 2016) and can estimate the strength of support for both the null and alternative hypotheses (Rouder & Morey, 2012). Analyses produce a Bayes Factor, BF_{10}, reflecting evidence favoring the alternative hypothesis. BFs_{10} larger than three were considered as evidence for the alternative hypothesis. Inconclusive BFs_{10} (i.e., between one-third and three) indicate lack of evidence for *either* hypothesis and that *more* data are needed (Kruschke, 2018). Bayesian parameter estimation with 95% credible intervals was then used to examine the uncertainty of estimated effects (Kruschke, 2018). Credible intervals that did not include zero (or in the case of log odds, that did not include 1) were considered evidence of the presence of an effect, conditional on the assumption that the effect exists (Kruschke, 2018). A small, standardized effect size (δ) was defined as $[0.2 \leq \delta < 0.5]$, which was reported with the frequentist Hedge's effect size (Cohen, 2013).

Results

Participant characteristics

Characteristics of the 632 sibling participants (207 NDC, 425 controls) are presented in Table 1. Most siblings were female (78.48%), from Australia (84.97%), and White (73.58%). The most common NDC was autism (24.15%).

Table 1. Characteristics of Sibling Participants.

Variable	Category	NDC n (%)	Control n (%)	Total N (%)
Sample		207	425	632
Participant age	Mean (SD)	19.81 (6.12)	20.90 (4.48)	20.54 (5.09)
	Range (years)	10–30	10–30	10–30
Participant gender	Female	161 (77.78)	335 (78.82)	496 (78.48)
	Male	46 (22.22)	90 (21.18)	136 (21.52)
Country of origin*	Australia	154 (74.40)	383 (90.12)	537 (84.97)
	Outside Australia (Europe, USA, Asia, Canada, New Zealand)	53 (25.60)	42 (9.88)	95 (15.04)
Ethnicity	White (Australian, European, New Zealand, American)	162 (78.26)	303 (71.29)	465 (73.58)
	Asian (Northern, Eastern, Southern)	15 (7.25)	97 (22.83)	112 (17.72)
	Other (Black African, Hispanic/Latino, Middle Eastern)	10 (4.83)	18 (4.24)	28 (4.43)
	Aboriginal Australian	20 (9.66)	7 (1.65)	27 (4.27)
Annual household income (AUD)	$0–$50k	57 (27.54)	72 (16.94)	129 (20.41)
	$51k-$100k	35 (16.91)	95 (22.35)	130 (20.57)
	$101k-$150k	38 (18.36)	46 (10.82)	84 (13.29)
	$151k+	23 (11.11)	75 (17.65)	98 (15.51)
	Unsure/Chose not to answer	54 (26.09)	137 (32.24)	191 (30.22)
Siblings' NDC	Autism	50 (24.15)	-	-
	ADHD	34 (16.43)	-	-
	Intellectual Disability	32 (15.46)	-	-
	Fetal Alcohol Spectrum Disorder	20 (9.66)	-	-
	Rett Syndrome	18 (8.70)	-	-
	Cerebral Palsy	16 (7.73)	-	-
	22q11.2 Deletion Syndrome	9 (4.35)	-	-
	Specific Learning Disorder	9 (4.35)	-	-
	MECP2 Duplication Disorder	8 (3.86)	-	-
	Epilepsy	7 (3.38)	-	-
	Other Chromosomal	4 (1.9)	-	-

Note: No participant siblings reported having more than one sibling with an NDC diagnosis. Only the primary diagnosis is reported, although 24% of participants reported their sibling had co-occurring intellectual disability with the first reported NDC.

Table 2. TBI and psychosocial functioning.

Variable	NDC	Control	BF_{10}	Effect size δ, 95% Credible Interval
Sample	207	425		
TBI History n (%)	31 (14.98)	27 (6.35)	0.35	−0.15 (−0.35, 0.06)
Gender (of those with TBI)			0.31	−0.05 (−0.58, 0.50)
Female n (%)	15 (48.39)	14 (51.85)		
Male n (%)	16 (51.61)	14 (48.15)		
Age (of those with TBI) M(SD) [range]				
TBI GCS M(SD) [range]	11.74 (1.71) [8–14]	12.33 (1.54) [9–15]	0.58	0.31 (−0.17, 0.82)
Mild (13–15)	13 (41.94)	13 (48.15)		
Moderate (9–12)	17 (54.84)	14 (51.86)		
Severe (3–8)	1 (3.22)	0 (0)		
Number TBI M(SD)[range]	2.06 (1.00) [1–4]	1.26 (0.53) [1–3]	6.20	−0.69 (−1.28, −0.13)
1 TBI, n(%)	11 (35.48)	21 (77.78)		
2 TBIs	10 (32.27)	5 (18.52)		
3 TBIs	7 (22.58)	1 (3.70)		
4 TBIs	3 (9.68)	0 (0)		
Age TBI M(SD)* [range]	13.74 (4.35) [5–22]	17.15 (4.41) [7–27]	5.39	0.62 (0.10, 1.17)
Time since last TBI (months) [range]	87.03 (51.12) [20–247]	70.48 (32.28) [24–139]	0.198	−0.20 (−0.69, 0.28)
At least one psychiatric diagnosis, n (%)	150 (72.46)	162 (38.12)	487437.51	−0.72 (−0.92, −0.54)
No psychiatric diagnoses, n (%)	57 (27.54)	263 (61.88)		
Autistic Traits M(SD) [range]	4.49 (2.43) [1–10]	3.25 (1.76) [1–10]	1595.01	−0.47 (−0.65, −0.30)
ADHD Traits M(SD) [range]				
Conduct Problems	2.43 (2.85) [0–15]	1.73 (2.20) [0–15]	0.65	−0.17 (−0.35, 0.01)
Hyperactivity.Impulsivity	3.17 (2.58) [0–9]	2.43 (2.34) [0–10]	6.12	−0.25 (−0.43, −0.08)
Attention Problems	5.36 (3.81) [0–12]	3.95 (3.23) [0–12]	41.98	−0.32 (−0.49, −0.16)
Alexithymia M(SD) [range]	19.05 (10.01) [0–40]	17.04 (7.89) [0–40]	1.69	−0.19 (−0.35, −0.04)
Parent-Child Relationship M(SD) [range]	22.25 (11.46) [0–40]	24.59 (10.28) [0–40]	0.82	0.17 (0.01, 0.33)
Sibling with a TBI** n(%)	33 (15.94)	13 (3.06)	1.48	−0.23 (−0.43, −0.02)

Note. TBI Glasgow Coma Scale (GCS) refers to the greatest severity reported by siblings for those with more than one TBI. * Reference to age of first TBI. ** Refers to the participants' sibling with the NDC (or the control group sibling) also having a TBI as reported by participants.

Aim 1. Characterisation of TBI

Of the NDC siblings, 14.98% self-reported TBI history, compared to 6.35% of controls (Table 2). The absolute risk difference was 8.63%. The posterior median of the relative risk of lifetime TBI for the NDC group compared to controls was 2.22 (95% credible interval 1.39–3.52), indicating sustaining a TBI is more likely in the NDC sibling group (see Supplementary Table S2). Of those with TBIs, severity was similar between groups, with 13 (41.94%) NDC and 13 (48.15%) control siblings reporting mild TBIs. More TBIs were reported by NDC siblings (two or more TBIs in 20 siblings; 64.52%) compared to controls (six siblings; 22.22%). Age of first TBI was younger in NDC than in control siblings. NDC siblings reported higher levels of autistic traits, hyperactivity/impulsivity, attention problems, and psychiatric diagnoses. Although effect sizes were moderate, there was insufficient evidence for group differences (BF_{10} <3) for conduct problems, alexithymia, and parent-child relationship. More participants in the NDC group with a TBI had a sibling with an NDC also with a history of TBI, compared to participants' siblings in the control group, as well as NDC siblings without a TBI.

Aim 2. Associations between psychosocial factors and TBI

Bayesian correlations revealed that, within the full sample, a history of TBI was associated with self-reported hyperactivity/impulsivity and inattention but not conduct problems, in addition to any psychiatric diagnosis and autistic traits (Table 3). More than one psychiatric diagnosis was associated with a higher probability of TBI. In the NDC siblings only, there was an association with conduct problems and weak evidence for an effect of parent-child relationship. Regarding

Table 3. Correlations Between Variables.

Variable 1	Variable 2	Kendall's tau b Full Sample	BF_{10}	Kendall's tau b NDC only	BF_{10}
TBI	Group (NDC or Control)	0.14*	55007.45	–	–
	Autistic Traits	0.09*	8.49	−0.01	0.09
	Conduct Problems	0.06	0.61	0.13*	3.59
	Hyperactivity/Impulsivity	0.08*	6.63	0.13*	4.97
	Attention Problems	0.08*	3.46	0.16*	42.26
	Alexithymia	0.03	0.09	0.09	0.63
	Any psychiatric diagnosis	0.08*	5.21	0.14*	6.74
	More than one psychiatric diagnosis	0.11*	163.12	0.18*	200.93
	Parent-Child Relationship	−0.03	0.09	−0.12*	2.96
	Male Sex	0.22*	$3.93 \times 10^{+13}$	0.30*	$4.624 \times 10^{+7}$
	Age	0.08*	2.80	0.08	0.42
	Minority Ethnicity	0.03	0.08	0.13*	5.32
	Household Income	−0.03	0.12	−0.18*	174.45
	Sibling TBI	0.29*	$4.15 \times 10^{+12}$	0.34*	$1.14 \times 10^{+10}$

Note. Frequentist significant correlations at $p < .05$ are flagged with *.

demographics, male sex was more likely to have a TBI history, as was older age and the participants' sibling having a TBI. In the NDC group only, minority ethnicity and lower income were associated with TBI. Subgroup analyses revealed that the TBI prevalence was driven predominantly by siblings of individuals with FASD (12, 20.69% of all TBIs) and autism (12, 20.69%), with a smaller group of ADHD siblings (7, 12.07%), with no other NDC sibling diagnostic groups represented with TBI.

Discussion

The present study characterized self-reported TBIs among siblings of individuals with and without NDCs and explored associations between TBI history and self-reported psychosocial functioning. There were three key findings. First, as hypothesized, NDC siblings had a higher proportion of TBIs, although there was uncertainty in this parameter and more data are needed in future studies. These TBIs were more frequent and sustained at earlier ages, in comparison to controls. In partial support of our second hypothesis, TBI history was associated with self-reported scale-based ADHD and autistic traits in the full sample, while in the NDC sibling TBI group, there was evidence for an association with self-reported conduct problems and poorer parent-child relationship. There was also partial support that minority ethnicity was associated with TBI in the NDC group only, and TBIs were only reported by siblings of persons with FASD, autism, and ADHD.

Characteristics of TBIs in NDC siblings

NDC siblings had higher rates of lifetime TBI (14.98%) than controls (6.35%), based on proportions alone. There was a lack of evidence for a difference in severity, with similar proportions from both groups reporting mild and moderate TBIs. Strikingly, however, most (64.52%) NDC siblings reported more than one TBI, compared to only 22.22% of controls. The mean age of first TBI was also substantially lower than that of controls. Within the NDC group, there was evidence of NDC specificity for TBI, not unexpectedly, given known disparities in psychosocial functioning of siblings of persons with FASD (Marquis et al., 2020; Wolff et al., 2023b) and autism (Pollard et al., 2013; Wolff, Magiati, Roberts, Pellicano, et al., 2022) compared to other NDCs and controls. This may, in part, reflect missed NDC diagnoses conferring greater behavioral risk factors (May et al., 2018; Sharma et al., 2018), yet also suggests there are environmental stressors and instability which compound risk of TBI in these families. For instance, there are high rates of adverse childhood experiences in households impacted by FASD, including substance misuse, domestic violence, bullying, and both accidental and inflicted TBIs, which contribute to poorer functional outcomes (Marquis et al., 2019; Tan et al., 2022).

Psychosocial factors associated with TBI in NDC siblings

Regarding individual-level factors, as hypothesized, NDC traits and psychiatric diagnoses were associated with history of TBI in the full sample, and these associations were stronger in the NDC sibling group than controls, other than autistic traits, likely due to group-level homogeneity. Psychiatric diagnoses were also associated with TBI, as expected from general population studies (Nelson & Stein, 2022). However, as the NDC group (including those without TBI) had high rates of psychiatric diagnoses, this likely reflects a predisposition to mental ill health, consistent with earlier reviews (Shivers et al., 2018; Wolff, Magiati, Roberts, Pellicano, et al., 2022). Although NDC siblings reported higher alexithymia than controls, this was not associated with TBI in our sample. Nonetheless, as alexithymia is prominent in both autism and TBI, it may be that a sub-group of these populations have specific clinical needs and experience unique risk factors (Kinnaird et al., 2019). Poorer parent-child relationship was associated with TBI, consistent with existing non-sibling youth literature (Fischer et al., 2022), although in NDC families this may also reflect parental mental health, stress, differential treatment, or NDC traits (Long et al., 2013).

Regarding structural determinants of health, although the sample was predominantly Caucasian, it is notable that Aboriginal ethnicity comprised 17.24% of the TBI group and 29.03% of the NDC TBI group (yet only 4.27% of the full sample). Aboriginal people are at over twice the risk of TBI, mechanism of injury is most commonly assault, with high mortality risk (Fitts et al., 2022; Katzenellenbogen et al., 2018) and high rates of discharge against medical advice (Fitts et al., 2019). There is a need to improve culturally-responsive prevention and rehabilitation services and develop more valid assessment tools (Lakhani et al., 2017). Racial health disparities and discrimination impacting family wellbeing may be compounded in families impacted by NDCs, with known cultural differences in acceptance and knowledge of NDCs (Viswanathan et al., 2022).

Lower income was associated with TBI in the NDC group only, highlighting the importance of equality of access to health education and services (Hayden et al., 2019). Previous general population studies conversely find that families of higher socioeconomic status experience greater burden, possibly due to higher health literacy, and monitoring of symptoms (Yeates et al., 2012). The high rates of participants' siblings' history of TBI in the NDC group also indicate shared family or environmental risk factors as well as genetic liability to traits which may increase TBI risk. Our study thus suggests that NDC siblings are disproportionately impacted by negative social determinants of health associated with TBI (Dams O'Connor et al., 2023).

Clinical implications

There are three clinical implications arising from the present findings. First, NDC siblings are at greater risk of TBI and sustaining injury at an earlier age, emphasizing the importance of medical practitioners routinely screening for possible TBI incidents from early childhood, minimizing situational and modifiable risk factors, and educating families. It is important to implement earlier education and training which promotes adherence to recovery, self-management strategies, and health literacy by providing accessible materials, and optimizing technology (e.g., online programs and telehealth) to reduce barriers to care (Pappadis et al., 2023).

Second, although directionality is unclear, it is plausible that *subclinical* NDC features (conduct problems, hyperactivity/impulsivity, inattention) predispose siblings to TBIs, indicating an NDC *diagnosis* is not necessary to confer risk. Clinical assessment of youth with mTBI is critical, due to differences in neurocognitive, behavioral, emotional and physical maturation, influences of home, school and community supports, and individual cognitive dispositions (Hou et al., 2023). NDC screening is thus important in clinical practice, particularly within subgroups characterized by higher rates of TBI in the general population, such as student athletes (Cook et al., 2023), minority ethnicities and disadvantaged individuals (Dams O'Connor et al., 2023), and juvenile justice settings (Schneider et al., 2021). Further, active ingredients in psychoeducational and behavioral interventions for TBI

(Fann et al., 2022), may differ for NDC siblings with TBI, for instance, problem-solving therapy may be helpful for siblings with compromised executive functioning, while mindfulness-based stress reduction may be more suitable for siblings functioning within a chaotic family environment.

Third, as a group, NDC siblings experience risk factors across the biopsychosocial framework at individual, family, and structural levels (Bronfenbrenner, 1995; Wolff, Magiati, Roberts, Pellicano, et al., 2022). Guidelines for managing TBI, while emphasizing that each recovery trajectory from TBI is unique and no single factor can predict outcomes, nevertheless recommend family education to optimize health literacy and behavior modifications (Lumba-Brown et al., 2018). Our own research has indicated that siblings benefit from interventions targeting family-level support (McKenzie Smith et al., 2018; Wolff, Magiati, Roberts, Skoss, et al., 2022), yet no TBI education programs address unique circumstances experienced by families with NDCs. Access to services and support for families experiencing external stressors, including instrumental support, may mitigate the impact of cumulative individual-level risk factors on sibling physical and psychological health, particularly for at-risk families within the FASD mesosystem (Reid et al., 2022). Online family-based interventions have proven effective in improving child and family outcomes in the context of TBI (Wade et al., 2019). Outreach and school-based programs may also be avenues for prevention or intervention.

Limitations

The present study was designed to focus solely on sibling self-report as part of a larger sibling project, hence TBI events and severity could not be verified. However, existing research suggests NDC siblings under-report mental health difficulties to minimize family burden (Rankin et al., 2017), which may also be the case with TBI. Although recall bias is a limiting factor, literature suggests adult recall of TBI history typically has low false positives (McKinlay et al., 2017) particularly when provided with a definition (Alosco et al., 2017). When neuroimaging becomes more accessible, future work may seek to disentangle neural atypicalities associated with NDC liability from changes in brain structure and function following TBI, to inform clinical models of recovery (Dennis et al., 2021).

Our sample was limited in generalizability, given most siblings from both groups were from Australia, of Caucasian ethnicity, and female. There may also have been selection bias wherein siblings with more severe TBI were unable to participate. Suitable comparator groups are also required. For instance, an orthopedic injury group could be recruited in future studies, to account for variance in outcomes following TBI due to general effects of trauma rather than brain injury per se (Nelson et al., 2019). Our study was cross-sectional, hence causality cannot be established between behavioral difficulties and TBI. Nevertheless, this may have important treatment implications; for instance, while stimulant medications are not a standard recommendation for treating cognitive deficits following mTBI, ADHD symptoms can be reduced with such medication and may serve to prevent incident TBI or improve recovery (Brunkhorst-Kanaan et al., 2021).

We did not have data on the context in which TBIs were sustained (i.e., inflicted or accidental injury), which may have provided further information to assist in person-level analysis of risk factors. Nor did we have estimates of pre-injury functioning, which is important given the baseline neurological, psychological, musculoskeletal and cognitive differences and diagnoses in individuals at risk of psychiatric conditions or NDCs (McCrory et al., 2017). Other factors impacting risk and recovery were not examined, such as family history (e.g., parental depression and anxiety, education history; Lumba-Brown et al., 2018). Cognitive effects of TBI may also result in poor awareness of impairments and reduced reliability of self-report (Dromer et al., 2021). Future research may consider using ecological momentary assessment as a tracking and treatment tool, rather than retrospective report data (Polinder et al., 2018).

Conclusion

Youth with TBI experience unique risk and resilience factors at the individual, family and structural levels (Babikian, 2022), and NDC siblings in particular have disproportionately high-risk factors

compared to controls (Wolff, Magiati, Roberts, Pellicano, et al., 2022). The clinical implication is that interventions for psychosocial risk factors associated with TBI may reduce TBI and improve recovery trajectories in NDC siblings, as well as functional and wellbeing outcomes. Many risk factors are modifiable and amenable to intervention and support. Positive outcomes following TBI are documented, particularly with increased access to health services, and family and social support (Shen et al., 2023). Improving policies and public-facing education for monitoring adverse childhood experiences and promoting resilient environments at the family and structural levels may mitigate risk of poorer functional outcomes following TBI (Fischer et al., 2022). There is a need for novel effectiveness studies with flexible approaches that consider the heterogeneity of both TBI and NDC sibling circumstances. This study forms a foundation for future longitudinal research to explore the mechanisms behind increased rates of TBI in these siblings, and the design of personalized prevention and intervention strategies for NDC siblings and families.

Notes

1. To identify if collinearity was problematic given the data, we estimated the marginal posterior densities of parameters using two priors, which did not produce a noticeable change in marginal posteriors; the Kolmogorov-Smirnov test confirmed univariate marginal posteriors converged (Assaf & Tsionas, 2021).
2. Note that all Bayesian analyses produce *relative* credibilities of parameter values or models under consideration, given the data. Prior predictive checks confirmed the priors generated simulated data consistent with assumed prior knowledge (Kruschke, 2021). Robustness checks were conducted to examine if our choice of priors influenced our findings. Analyses using wide (1.0) or ultrawide priors ($\sqrt{2}$) did not alter the direction of results, hence these findings were considered robust to reasonable changes in prior width given the data. Sequential Bayes Factor analyses conducted in rjags for each independent variable did not indicate support for the opposite hypothesis at any sample size.

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Pre-registration

This study was pre-registered: https://osf.io/8wytd

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Author contribution

EG obtained funding. BW conceived the present manuscript, analyzed the data, and produced the first draft. All authors critically revised and reviewed the final manuscript.

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