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CHILDHOOD TRAUMATIC BRAIN INJURY AS A RISK FACTOR FOR ADOLESCENT DELINQUENT BEHAVIOR

A Thesis in

Criminology

by

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ABSTRACT

Some of the most commonly experienced emotional and behavioral issues following a traumatic brain injury (TBI) are increased impulsivity and aggression (Yeates and Taylor 2005), both of which are strongly correlated with criminal behavior (Perron and Howard 2008; Vaughn et al. 2014). The experience of a TBI at any point in the lifespan has the potential to dramatically change subsequent behaviors; however, in conjunction with ongoing neurodevelopment in childhood and adolescence, a TBI that occurs during this key developmental period may be even more detrimental for health risk behaviors (Karver et al. 2012). In particular, childhood TBI might be a serious risk factor for a variety of behavioral changes, including antisocial or delinquent behaviors. Developmental and life-course (DLC) theories of crime suggest that disruptions to normative development—such as those precipitated by TBI—during childhood increase risk for later criminal behavior (Farrington 2006; Moffitt 1993; Moffitt and Caspi 2001). Alternatively, childhood TBI and adolescent delinquent behavior could share several early-life risk factors, such as maternal substance use during pregnancy or childhood conduct disorder—that would confound the proposed relationship by increasing the risk for both TBI and delinquent behavior.

Although research consistently finds associations between TBI and criminality, much is not known about the nature of the relationship, including whether the relation is spurious or differs by sex. In this thesis, nationally representative prospective data from the UK Millennium Cohort Study (MCS) are used to examine the relationship between early-life risk factors, TBI, and delinquent behavior for both males and females. Results appear to be consistent with DLC theories of crime, in that childhood TBI is significantly associated with early onset delinquency (age 11) but not with onset of more adolescent-typical delinquency (age 14). However, childhood TBI is significantly associated with participation in a greater variety of delinquent behaviors at age 14 and sustained delinquent behavior from age 11 to age 14 years. These results suggest that TBI may be predictive of early onset and more serious delinquent behavior in adolescence but not relatively minor or normative delinquent behavior. Additional exploratory analyses are conducted to explore nuance and motivate future research of these relationships.

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INTRODUCTION

The psychological, emotional, and behavioral complications that arise after experiencing a traumatic brain injury (TBI) are numerous and potentially severe (Crowe 2008; Eslinger, Flaherty-Craig, and Benton 2004; Karver et al. 2012; Yeates and Taylor 2005). Damage to the brain often impacts executive functioning, which includes abilities such as inhibition, decision-making, and emotional regulation (Barker et al. 2010). It is no surprise then that some of the most commonly experienced emotional and behavioral issues following a TBI are increased impulsivity, confusion, and aggression (Yeates and Taylor 2005). Executive function deficits, especially increased impulsivity and aggression, are often implicated in criminal behavior, which provides a potential link between TBI and criminal behavior (Moffitt 1993; Moffitt and Caspi 2001; Perron and Howard 2008; Vaughn et al. 2014). Furthermore, the heightened prevalence of TBI in offender populations is well-established within the literature, with prevalence estimates of TBI averaging about 46% for offender populations, compared to about 12% for the general population (Durand et al. 2017; Frost et al. 2013; Huw Williams et al. 2010; Kaba et al. 2014; Perron and Howard 2008). Research consistently finds associations between TBI and criminality (Durand et al. 2017; Fishbein et al. 2016; Huw Williams et al. 2010; Kaba et al. 2014; Luukkainen et al. 2012; Schofield et al. 2015; Schwartz, Connolly, and Brauer 2017), but this relationship has not fully been explored in adolescent populations. While it is generally proposed that damage to brain tissue can precede criminal behavior, few studies have examined this relationship longitudinally. Furthermore, while no experimental studies have been conducted on humans (due to obvious ethical complications), studies of mice with mechanically induced head injuries do support a causal relationship between head injury and antisocial behavior (see Hiskens et al. 2019 for review: also Guilhaume-Correa et al. 2020; Zhao et al. 2018). In humans, it is unclear how much of an effect brain injury actually has on antisocial behavior and, as is the aim of this thesis, whether this damage is related to adolescent delinquent behavior, net other early-life risk factors.

Developmental and life-course (DLC) theories of crime suggest that disruptions to key developmental milestones during childhood should influence later criminal behavior (Farrington 2006; Moffitt 1993; Moffitt and Caspi 2001). DLC theories have historically placed more emphasis on environmental and contextual risk factors, but recent research finds support for the importance of biological risk factors—such as the tissue damage following a TBI—during critical developmental periods (Eslinger et al. 2004; Karver et al. 2012). While TBI at any point in the lifespan has the potential to dramatically change brain functioning and subsequent behaviors, TBI that occurs in either childhood or adolescence may be even more detrimental to normative development (Guilhaume-Correa et al. 2020; Zhao et al. 2018). During this time, the brain goes though marked changes in both structure and function, making it more susceptible to environmental influences (Karver et al. 2012).

Following Moffitt's dual taxonomy theory, individuals who experience some sort of early-life trauma, such as a TBI, should be more likely to initiate delinquent behavior early and engage in more serious delinquent behaviors (Moffitt 1993; Moffitt and Caspi 2001). Part of this increased likelihood of serious delinquency could be due to the behavioral and neurological changes that arise from damage after a TBI. Although the present study is unable to directly associate specific clinical brain tissue damage with neuropsychological change, the relationship between general childhood brain injury and onset patterns of delinquent behavior will be examined.

Research on the behavioral correlates of TBI tends to fall under the purview of either clinical or criminological research. These two fields offer relatively different perspectives and foci on the study of TBI, sometimes to the detriment of further progress in TBI research. Clinical literature tends to focus on moderate to severe TBIs, which are much less common than mild TBIs (Frost et al. 2013), and criminological literature tends to focus on offenders with a history of TBI, which introduces selection issues (Schwartz et al. 2017). While clinical samples provide useful insights on the potentially severe effects of TBI, they are not representative of the general population that experiences a TBI. It has been estimated that up to 50% of people with mild TBIs—which are far more common than their more severe counterparts—do not seek medical attention (Demakis and Rimland 2010), leaving much of the population with TBIs outside of the scope of clinical studies. On the other hand, criminological studies of offender populations shed light on how prevalent head injuries are among convicted criminals but do little to address whether TBI has any influence on initiation and persistence of criminal behavior or whether TBIs are a side effect of involvement in criminal and potentially dangerous behavior. Additionally, the use of convicted samples in criminology research excludes those who have a history of TBI but have not come into contact with the criminal justice system.

Furthermore, methodological complications exist in the study of TBI, many of which involve the operationalization of the injury variable itself. Within clinical studies, many studies use diagnostic scales, which allow for relatively precise measures of TBI severity (Bonow et al. 2019; Light et al. 1998; O'Sullivan et al. 2015; Yeates and Taylor 2005), while criminological research tends to rely on self-reports of TBI history, which introduces potential issues with construct validity (Kennedy, Heron, and Munafò 2017; Perron and Howard 2008; Vaughn et al. 2014). Another major area of discrepancy between clinical and criminological research is the use of reference groups. Clinical studies often use a measure of other orthopedic or bodily injury as a control group, while criminological studies tend to compare those with TBI to their non-injured peers. The use of the orthopedic injury reference group has been recommended for future studies on TBI as its use accounts for omitted variables that might influence the risk of experiencing any sort of bodily injury as well as the risk for the antisocial behavioral outcomes of interest (Karver et al. 2012; Milders et al. 2008; Yeates and Taylor 2005). Furthermore, both areas of study have offered relatively limited examinations of potential sex differences in behavioral change following a TBI. This particular limitation is largely due to insufficient sample sizes, so it is unclear whether and how sex differences might arise after TBI.

To address the gaps in this body of knowledge and some of the limitations in the extant literature discussed above, I have accessed nationally representative, prospective data from the UK Millennium Cohort Study (MCS). These data will allow me to examine the effect of childhood TBI on adolescent delinquent behavior in the general population. The MCS follows the lives of over 18,000 children and their families to gain insight on physical, social, cognitive, and behavioral development throughout the new millennium (Connelly and Platt 2014; Joshi and Fitzsimons 2016). At the initial wave, cohort members were 9 months of age. Subsequent waves of data have been collected at ages 3, 5, 7, 11, and 14 years, with data from age 17 years to be released later in the year. Data from all released waves (i.e., up to age 14) are used in the present study.

The focal analyses of the current study examine the effect of TBI on age of delinquent behavior initiation and patterns of delinquent behavior, while accounting for early-life risk factors consistent with DLC theories of crime. Parent reports of cohort members' experiences of TBI at multiple ages provide a unique non-clinical sample, while self-reports from the cohort members provide information on delinquent and antisocial behaviors. Supplementary analyses aim to explore sex differences and developmental period effects to further refine the relationship between childhood TBI and delinquency. This thesis aims to contribute to the fields of biosocial and DLC criminology by parsing out the effects of childhood TBI on adolescent delinquent behavior, while accounting for other important early-life risk factors and incorporating relevant methodological considerations from clinical studies of TBI.

LITERATURE REVIEW

Theoretical Perspectives

Within the developmental and life-course (DLC) framework, two theories are particularly relevant to childhood head injury. Moffitt's theory of antisocial behavior and Gottfredson and Hirschi's theory of self-control both posit that early life factors influence later behaviors, specifically delinquency (Gottfredson and Hirschi 1990; Moffitt 1993). Moffitt's (1993) original conceptualization of dual taxonomy theory implicates head injury resulting from child abuse as a possible source of neuropsychological deficits and later criminal behavior. Recent biosocial research has further opened the door to incorporating neurobiological mechanisms, such as executive functioning and self-regulation, as influential in the emergence of delinquent behavior (Beaver et al. 2010; Beaver, Wright, and Delisi 2007).

Moffitt's theory of antisocial behavior outlines two distinct trajectories of delinquent behavior—the life-course persistent and adolescent-limited pathways (Moffitt 1993; Moffitt and Caspi 2001). For those who are life-course persistent offenders, Moffitt theorized that some biological or early life traumas influenced their delinquent behavior and that this delinquent behavior would start earlier and continue later than their adolescent-limited peers. Those early life traumas distinguish the life-course persistent offender from the normal and routine delinquent behavior of adolescent-limited offenders, as well as from those who do not exhibit delinquent behavior (Moffitt and Caspi 2001; Nagin, Farrington, and Moffitt 1995). Moffitt and Caspi (2001) identified several influential risk factors for life-course persistent offending, such as IQ, temperament, verbal skills, and "neurological abnormalities." Moffitt's original conceptualization of the dual taxonomy theory briefly mentions head injury as a possible source of neuropsychological deficits through childhood abuse (Moffitt 1993); however, to my knowledge, it has not frequently been included in recent tests of the theory. Head injury may distinguish between life-course persistent offenders and those who do not offend, as well as for those who are childhood-limited offenders (Raine et al. 2005). There is mixed evidence for whether head injury can distinguish between life-course persistent and adolescent-limited offenders (Raine et al. 2005); although some of this inconsistency may be due to samples or operationalizations of head injury.

Moreover, Moffitt originally focused on disruptive events that occur during fetal development or perinatally (i.e. the first several weeks after birth) as major risk factors for later persistent delinquency (Moffitt 1993). Building upon this work, increasing evidence from developmental science suggests that risk factors can and do occur throughout childhood and into adolescence (Miller, Malone, and Dodge 2010; Moffitt and Caspi 2001; Pepler et al. 2010). Furthermore, there may be critical points in development throughout childhood and adolescence when vulnerability to both environmental and biological risk factors is accentuated (Casey, Giedd, and Thomas 2000; Eslinger et al. 2004; Karver et al. 2012). The "latent deficit" hypothesis suggests that early childhood traumas will produce worse and longer-lasting cognitive deficits than adult injuries of the same magnitude due to heightened sensitivity of the brain (Barker et al. 2010; Eslinger et al. 2004). Studies in mice with mechanically induced head injuries provide support for this hypothesis, as neuropsychological deficits are more severe in adolescent than adult mice (Guilhaume-Correa et al. 2020; Zhao et al. 2018).

One of the mechanisms through which TBI could potentially increase the risk of delinquent behavior is via impacts on executive functioning. One of the hallmarks of executive dysfunction is impulsivity or lack of self-control. Gottfredson and Hirschi's theory suggests that self-control begins to emerge in childhood and that a lack of self-control, in conjunction with an opportunity structure conducive to negative outcomes, increases risk for criminal behavior (Akers 1991; Gottfredson and Hirschi 1990). They originally theorized that the development of self-control was directly related to socialization from parents during childhood and was fully determined before adolescence (Gottfredson and Hirschi 1990). Furthermore, they predicted that an individual's self-control remains relatively constant over the lifespan after the socialization process has completed.

While the specific origins of self-control are still debated, research from neuroscience and biosocial criminology find evidence that self-control is influenced by other genetic and biological factors as well as social factors (Beaver et al. 2010, 2007). Specifically, neuroscience research supports the premise that self-control—along with other executive functions—is primarily regulated by the prefrontal cortex of the brain and its role in modulating emotional responses of the limbic system (Crowe, 2008). Neuropsychological deficits in childhood are related to both levels of adolescent self-control and delinquency (Beaver et al. 2010, 2007). Thus, neurological deficits that arise as a result of damage to the brain during childhood have potential to negatively impact the development of an individual's self-control, and consequently, their propensity for delinquent behavior.

Alternatively, Gottfredson and Hirschi's theory of self-control argues that low self-control also increases the likelihood of accidents or injuries (Gottfredson and Hirschi 1990). Early levels of self-control might have an impact on an individual's likelihood of getting a TBI—or any injury, for that matter—later in childhood. Individuals who are more impulsive may be more likely to exhibit behaviors that could lead to both delinquency and any type of injury—not just head injury. Therefore, it is important to consider how low self-control—and many of the social factors that are theorized to influence self-control—may contribute to the risk of injury and the risk of delinquency. A bidirectional relationship between TBI and self-control is very likely and, therefore, is important to account for in tests of TBI effects on delinquency. While the present study is unable to test self-control as a possible mediator of the relationship between TBI and delinquency, adjustments for level of self-control are included in several ways. Notable early-life risk factors that influence development of self-control are accounted for, as well other pre-morbid characteristics that could lead to bodily injury.

Traumatic Brain Injury and Crime

TBI is the most common form of injury to the brain. According to Crowe (2008), a TBI occurs when “the brain is damaged when the force of [an external] impact causes it to smash against the bony surfaces on the base of the skull” (p.9). TBI are usually limited to closed head injuries, such that the bones of the skull are not fractured. Many different scales are used in clinical settings to classify the severity of a TBI, such as the Glasgow Coma Scale (GCS) or the Ohio State University Traumatic Brain Injury Identification Method (OSU TBI ID). Many of these scales use the presence and duration of unconsciousness, amnesia, and confusion post-injury to determine severity of the injury. Mild concussions represent the most common forms of TBI. These characteristics of TBI are often a major focal point of clinical research but are frequently overlooked in criminological research in favor of other correlates.

Studies in criminology have consistently found TBI to be associated with impulsivity, aggression, and substance use (Fishbein et al. 2016; Huw Williams et al. 2010; Perron and Howard 2008; Schwartz et al. 2017; Vaughn et al. 2014). Huw Williams and colleagues (2010) found that frequency of self-reported TBIs were associated with a greater number of convictions and more mental health problems in male adolescent offenders. In another sample of delinquent adolescents, a history of TBI was found to be associated with being male, mental health diagnoses, impulsiveness, and earlier onset of both criminal behavior and substance use (Perron and Howard 2008). In a similar study of adolescent offenders, Vaughn et al. (2014) reported that TBI was more prevalent in males and associated with higher levels of impulsivity and negative emotions.

Although connections between TBI and crime have been examined, past studies predominately focused on the high prevalence of TBI in offender populations rather than the predictive validity of TBI for criminal behavior (Durand et al. 2017; Farrer, Frost, and Hedges 2013; Farrer and Hedges 2011; Huw Williams et al. 2010; Perron and Howard 2008). Both Durand et al. (2017) and Fazel et al. (2011) established that the prevalence of TBI in adult incarcerated groups is significantly higher than that of the general population. Durand and colleagues (2017) concluded that the average prevalence of TBI in prison populations is 46%, but some estimates have exceeded 60% (Farrer and Hedges 2011). Among juvenile offenders, the prevalence of self-reported TBI ranges from 18-75% (Farrer et al. 2013; Huw Williams et al. 2010; Perron and Howard 2008). The large ranges for these estimates are likely due to inconsistencies in operationalizing head injury across studies.

A couple of studies have sought out to link TBI history with delinquent and antisocial behavior. Fishbein et al. (2016) examined the relationship between childhood TBI, substance use and aggression in a sample of incarcerated adults. Childhood TBI was associated with earlier initiation into illicit substance use than those without TBI or with TBI occurring later in life. A history of TBI was associated with higher levels of aggression but did not differ between those who had childhood TBIs or later-life TBIs. Schwartz, Connolly, and Brauer (2017) examined the link between head injury, self-control, and delinquency in adjudicated adolescents. Self-reported TBI was associated with lower levels of self-control, as well as higher rates of aggression and delinquent behaviors. Since both of these studies utilize samples of known and detained offenders, associations between TBI and antisocial or delinquent behaviors might be underestimated, as the variation in outcomes of interest is reduced.

Studies that have attempted to examine the causal ordering of TBI and delinquency in the general population are relatively rare. To my knowledge, there are only four studies that have attempted to assess TBI as a cause of criminal behavior in nationally representative samples (Bonow et al. 2019; Fazel et al. 2011; Kennedy et al. 2017; Timonen et al. 2002).

The Northern Finland Birth Cohort Study examined whether TBI in childhood was associated with alcohol use, psychiatric disorders, and criminal behavior in adulthood using a population birth cohort (Timonen et al. 2002). Respondents with TBI were identified from hospital discharge registers and were matched with controls who had never experienced a TBI. In this study, TBI included "skull fracture, cerebral contusion and concussion and intracranial injuries" (Timonen et al. 2002:218) The longitudinal nature of this study allowed analyses to be restricted to TBI that occurred prior to any reported criminal behavior, which helps support their argument of TBI as a cause of criminal behavior. Findings suggest that childhood TBI is associated with a 60% increase in the odds of later criminal behavior. Furthermore, TBI that occurred before age 12 was associated with earlier age of onset of criminal behavior. This study suffered from a methodological limitation in that individuals with TBI were compared to uninjured individuals, which may lead to overestimations of TBI effects (Yeates and Taylor 2005). Additionally, as TBI is defined by clinical diagnostic criteria, individuals with TBI may represent a more severely injured subsample, which limits the generalizability of the results.

The second study of note is a 35-year Swedish Population study that examined the risk of violent criminal behavior in individuals with epilepsy or TBI (Fazel et al. 2011). National registers on general population, health, and crime were used to form a sample of individuals over the age of 15 years. TBI was based on near identical diagnostic criteria as the Timon et al. (2002) study. Respondents with TBI were matched with general population controls, as well as uninjured siblings when possible. Individuals with TBI were 3.3 times more likely to commit a violent crime after their diagnosis compared to the matched controls. This study suffers from limitations similar to the study described above, including the use of a clinical sample of TBI patients and an uninjured comparison group. Clinical samples of TBI patients may represent more severe injuries than non-clinical samples, as those with milder head injuries may not choose to receive medical care (Demakis and Rimland 2010).

As briefly mentioned, both studies utilized controls without any prior injuries. Yeates and Taylor (2005) have suggested the use of individuals with an orthopedic injury as controls in future studies of TBI. The use of an injured control groups should account for any underlying factors that may contribute to behaviors that lead to possible injury, whether to the head or the body. In their theory of self-control, Gottfredson and Hirschi (1990) mention the possibility that low- self-control may lead to accidents and injuries, as well as delinquent behavior. It is also plausible that there are other factors that may influence the likelihood of experiencing an injury, outside of the risk factors that are overtly controlled in analyses. Additionally, it is possible that the experience of an injury—any injury—may modify behavior in unobserved ways. For instance, an injury to a child, whether to the head or the body, might increase the level of supervision by a parent, which would decrease criminal behavior. By having a negative control injury group, those unobserved factors should be accounted for implicitly (Karver et al. 2012; Yeates and Taylor 2005).

Following that recommendation, Kennedy, Heron, and Munafo (2017) examined the link between TBI and later criminal behavior in a longitudinal birth cohort sample. Cohort members were categorized as having a TBI, an orthopedic injury, or no injury. TBI was defined as either loss of consciousness or fracturing the skull, while OI was defined as breaking any other bone in the body (Kennedy et al. 2017:1198). Compared to uninjured individuals, those with TBI were approximately 30% more likely to have committed a criminal offense and about 17% more likely to have been in contact with the police by age 17. However, when compared to individuals with an orthopedic injury, neither of those associations remained statistically significant. While this study does address many issues of prior studies, it does still have a couple of limitations. The measure of criminal behavior is limited to serious offenses and contact with police, leaving out many less serious delinquent behaviors. Additionally, the authors do not account for any earlier criminal behavior or victimization experiences that could have led to TBI or orthopedic injury and confounded the relationships of interest.

The final study of note is a retrospective cohort study using administrative records on hospitalizations and arrest records of adults in the state of Washington (Bonow et al. 2019). The TBI groups was defined by an *ICD-9 CM* diagnosis code for TBI. An orthopedic injury group was defined by the any other injury-related *ICD-9 CM* diagnosis code. The uninjured group included all hospital admissions without injuries, such as those with psychiatric disorders, other illnesses, or routine surgical procedures (Bonow et al. 2019:62). Hazard ratios for arrest following hospital discharge were calculated. Compared to uninjured patients, those with TBI had a 57% increase in the risk of being arrested following their discharge from the hospital. When compared to patients with orthopedic injuries, there was no significant association between TBI and likelihood of future arrest. This study provides further evidence that a negative control injury group is needed in studies of TBI and criminal behavior. A major strength of this study was the ability to account for arrests that occurred before injury. On the other hand, the use of administrative arrest data does limit the criminal behavior examined. Only those who have had contact with the criminal justice system would be included in that data. Additionally, the use of administrative data precludes any information on individuals prior to age 18 (or 15, in the case of Fazel et al. 2011), including prior head injuries and juvenile delinquent behavior.

All of these studies provide support for TBI as an important predictor of criminal behavior. In recent years, studies of the relationship between TBI and criminal behavior have provided great insight to a previously understudied phenomenon. However, there are still gaps in the literature that should be explored, such as further explorations of the relationship in adolescent populations. Given the importance of sensitive developmental periods in childhood and adolescence, it stands to reason that head injury during those sensitive periods may lead to more detrimental outcomes than head injury that occurs in adulthood. To my knowledge, no study has yet had the opportunity to explore possible variation in the relationship between TBI and criminal behavior due to injury at certain developmental periods; however, this need has been discussed in other studies (Bonow et al. 2019; Kennedy et al. 2017) and is theoretically important (Moffitt 1993; Moffitt and Caspi 2001; Odgers et al. 2008).

Additionally, studies have yet to explore possible sex differences, largely due to insufficient samples sizes of females with either TBI or criminal histories. Females who have a history of TBI may exhibit similar levels of violent behavior to males (O'Sullivan et al. 2015). Findings have been largely mixed and have led to calls for more research on TBI in both female non-offender and offender populations in order to determine what differences and similarities exist (Williams, 2012). Prevalence rates appear to be relatively similar between incarcerated males and females (Fishbein et al. 2016; Kaba et al. 2014), even though being male may be a risk factor for experiencing a TBI (Perron and Howard 2008; Vaughn et al. 2014).

The Current Study

To address several of the limitations identified above, as well as to extend previous findings to an adolescent population, the current study seeks to examine the relationships between early-life risk factors, TBI, and delinquent behavior. The first step of the analysis determines whether certain early-life risk factors predict whether a child will experience a TBI or OI. Although OI is used to control for unobserved injury-related characteristics—such as low baseline self-control—it is possible that some early-life risk factors are more predictive of one type of injury than the other. Additionally, this phase of the analysis will also examine whether these early-life risk factors for injury vary by sex. The second step of the analysis examines whether childhood TBI is a significant predictor of onset and typology of adolescent delinquency, even when compared to individuals with other bodily injuries. To my knowledge, no other study has addressed onset and typology of delinquent behavior, while also controlling for the pre-morbid injury-related factors that could confound the relationship between crime and TBI. The use of the Millennium Cohort Study allows for in-depth analyses of these relationships in a nationally representative and non-clinically defined sample. Several hypotheses are considered:

Hypothesis 1: A history of childhood TBI will predict higher levels of delinquency than the absence of childhood TBI. In contrast, childhood TBI, when compared with childhood orthopedic injury (OI), will predict higher levels of delinquency, albeit to a lesser extent.

Following recommendations from previous studies (Bonow et al. 2019; Karver et al. 2012; Kennedy et al. 2017; Milders et al. 2008; Yeates and Taylor 2005), OI is used as a comparison to TBI. OI represents a negative control injury group, which should account for many pre-morbid characteristics leading to injury, as well as possible external environmental changes post-injury. As prior studies have indicated that the effects of TBI are attenuated when comparing to OI, I expect to see similar patterns.

Hypothesis 2: Childhood TBI will be more predictive of early-onset delinquency at age 11 than of adolescent-onset delinquency at age 14.

Hypothesis 3: Childhood TBI will increase the risk of sustained delinquent behavior from age 11 to age 14, as well as the risk for a greater variety of delinquent behavior at age 14.

Both Hypothesis 2 and Hypothesis 3 are strongly motivated by Moffitt's dual taxonomy theory. Early-life risk factors, including head injury, should be predictive of early-onset delinquent but not necessarily predictive of adolescent-onset delinquency (Moffitt 1993; Moffitt and Caspi 2001). Instead, adolescent-onset delinquent may be more influenced by psychosocial factors, such as peer deviance. However, childhood TBI should still be predictive of more serious delinquent behavior, such as consistency in behavior from age 11 to age 14 and participation in a greater variety of delinquent behavior.

Additional analyses will examine possible sex differences and developmental period effects. It is unclear whether TBI vary in its effect on delinquent behavior between males and females (O'Sullivan et al. 2015), although some studies do find sex differences in severity of substance use (Fishbein et al. 2016) and expression of externalizing and internalizing problems (Scott et al. 2015). Supplementary analyses are used to determine robustness of estimates, even when using either a different operationalization of head injury or externalizing behavior as an outcome.

DATA AND METHODS

Data

The Millennium Cohort Study (MCS) is a longitudinal and nationally representative study of children born in the UK from 2000 to 2002 (Plewis 2007). Infants included in the survey were living in either England, Wales, Northern Ireland, or Scotland at the time of the initial wave (Joshi and Fitzsimons 2016). The MCS oversampled children exposed to higher levels of disadvantage, including electoral wards with high levels of poverty (Connelly and Platt 2014). At the initial wave, which occurred when cohort children were modal age 9 months, parents from 18,552 families participated in questionnaires and in-person interviews, producing a total sample of 18,818 children (Plewis 2007). At the second wave (modal age 3), an additional 1,389 families were added to the survey to account for otherwise eligible families who were not included in the initial wave.

By age 14, about 76% of MCS children were still able and willing to participate. Attrition was more likely among boys, Whites, children of parents with lower levels of education, and children in single-parent households (Mostafa and Ploubidis 2017). The MCS did not consider injury status in assessments of attrition likelihood. In Appendix A, Table A1 presents a bivariate logistic regression of injury status from ages 3 to 11 years on attrition from wave 5 (modal age 11) to wave 6 (modal age 14). TBI is not significantly associated with whether or not an individual stopped participating in the survey.

In-home interviews and assessments were conducted with MCS cohort members and their caregivers at six total waves. Computer-assisted personal interview (CAPI) and computer-assessed self-interview (CASI) were used to collect data (Fitzsimons 2017). Interviews were conducted with the primary caregivers regarding the household, their own behaviors, and the cohort member's behavior. In the vast majority of cases (98%), the main caregiver was the cohort member's natural mother (Fitzsimons 2017). Data were collected when the children were modal ages 9 months, 3, 5, 7, 11, and 14 years old. Data from age 17 is forthcoming. At ages 11 and 14, the MCS cohort members were administered confidential CASI surveys to assess their attitudes and participation in risky behaviors.

The MCS collects a large breadth of information from both the cohort members and their parents. For the present study, I utilized measures focusing on early-life behaviors, maternal behavior during pregnancy, health and wellness, and delinquent behavior during adolescence, as well as a broad array of sociodemographic characteristics. Descriptive statistics for the variables of interest in the present study are shown in Table 1. Analytic samples for both age 11 (wave 5) and age 14 (wave 6) are presented. The samples are weighted based on weights unique to the wave that account for sampling strata and the oversampling of disadvantaged families throughout the UK, as well as sample attrition.

Table 1. Weighted Descriptive Statistics

	Age 11 Sample N=13,287		Age 14 Sample N=11,714	
	Mean or Percentage	*SE*	Mean or Percentage	*SE*
Injury Status (ages 3-11)				
Traumatic Brain Injury	27.2%		27.2%	
Orthopedic Injury	40.2%		39.7%	
No Injury	32.6%		33.1%	
Delinquency (age 11)	31.2%		31.3%	
Delinquency (age 14)			57.8%	
Variety of Delinquent Behaviors (age 14)			1.24	*0.026*
Sustained Delinquency (ages 11 & 14)			22.4%	
Early-Life Risk Factors (age 9 months)				
Low Birthweight (<2.5kg)	3.8%		3.9%	
Birth Complications	32.0%		31.0%	
Neurological Deficits	4.8%		4.7%	
Maternal Smoking Behaviors				
Never Smoked During Pregnancy	63.0%		61.2%	
Stopped Smoking During Pregnancy	12.9%		12.8%	
Smoked Throughout Pregnancy	24.1%		25.9%	
Maternal Alcohol Use During Pregnancy	30.9%		30.2%	
Clinical Hyperactivity (age 3)	12.7%		13.3%	
Clinical Conduct Problems (age 3)	28.5%		29.3%	
Cognitive Abilities (age 3)	47.58	*0.637*	46.45	*0.664*
Highest Parental Education	2.65	*0.033*	2.58	*0.033*
Race/Ethnicity				
White British	84.4%		85.3%	
Asian British	7.1%		7.4%	
Black British	3.5%		4.1%	
Other British	5.0%		3.2%	
Male	51.6%		52.4%	
Age	10.67	*0.006*	13.78	*0.006*

Injury Status

At each wave of the survey, primary caregivers of the MCS cohort children are asked what injuries their child had experienced since the last wave. Children were coded as experiencing a TBI if either “loss of consciousness/knocked out” or “bang on the head/injury to head without being knocked out” was reported. These criteria for head injury remained constant across all waves. Caregivers were able to report multiple injuries within a given wave. Expected demographic patterns are consistent throughout each wave, with boys reporting more injuries overall and more head injuries than girls (Table 2). Injuries that were reported between the ages of 3 and 11 are included in the analyses in order to isolate this predictor to injuries that would have primarily occurred before the reported delinquent behaviors.

Table 2. Injury Status at Age 14, by Sex

	Males N = 5877	Females N = 5837
Injury Status (ages 3-11)		
Traumatic Brain Injury	32.50%	21.40%
Orthopedic Injury	37.30%	42.30%
No Injury	30.20%	36.20%

In contrast to many other studies of outcomes after TBI, the MCS cohort does not constitute a clinical sample. That is, the cases included in this model may not have visited the hospital and been assessed as having either a mild, moderate, or severe TBI based on a diagnostic scale. However, there are some benefits of using a non-clinical sample. Namely, about half of people who experience a TBI will not go to the hospital, which limits the samples that are traditionally included in clinical samples (Demakis and Rimland 2010). By using a non-clinical sample, the effects of reported TBIs might be more generalizable; however, they may lack some of the magnitude of studies using more severe TBIs. Additionally, they may be subject to social desirability bias, in which case, parents may underreport their children's injuries.

Following previous literature, individuals with a history of Orthopedic Injury (OI) are included as a comparison group to those with TBI (Kennedy et al. 2017; Milders et al. 2008; Yeates and Taylor 2005). Whether an individual experienced an OI or not was determined from all of the other injury-related responses to the same question(s) used to determine experience of a TBI. In the questionnaire, OIs were limited to significant injuries, such as broken bones or animal bites. Minor wounds or scrapes were not included in the original wording of the question. OIs were reported more frequently at each wave than TBIs, which is to be expected. By using OI as a foil, other pre-morbid effects or injury-related factors that might be contributing to the relationship between TBI and delinquency are considered and accounted for implicitly, assuming that there is no difference between those who received OIs and TBIs. Furthermore, if TBI predicts delinquency but OI does not, then a unique relationship between head injury and delinquency might exist that does not generalize to other bodily injuries. In other words, there may be something inherently different about how head injury leads to delinquency above and beyond whatever spurious mechanisms, including social factors, lead to both bodily injury and criminal behavior.

Individuals were coded as having No Injury (NI) if no injuries were reported at any of the waves from ages 3 to 11. If an individual had reports of both OI and TBI at either the same wave or different waves, they were coded to belong in the TBI group, as is common in other studies (Bonow et al. 2019; Kennedy et al. 2017). Individuals within the TBI group may have experienced both TBI and OI, but the use of the OI group as a control should account for any of the injury-related factors that are present in both groups. As shown in Table 1, approximately 27% of children experienced a TBI from ages 3 to 11. Approximately 40% experienced an OI from ages 3 to 11, and approximately 33% never experienced either a TBI or an OI.

In supplemental analyses, an alternative coding scheme for head injury is used. TBI is still defined as either “loss of consciousness/knocked out” or “bang on the head/injury to head without being knocked out.” The comparison group is all individuals who did not report a TBI (nTBI). This group would include those who never report an injury and those who report only bodily injuries. This coding scheme mirrors those frequently used in criminological literature that do not take OI into account (Perron and Howard 2008; Vaughn et al. 2014).

Delinquency Onset

Age 11 delinquency is used to obtain an indicator of early initiation into delinquency, while age 14 is used as a measure of more normative delinquency. Measures from the age 11and 14 questionnaires ask about cohort members' own delinquent behaviors. Delinquency at age 11 was coded as a binary measure of whether the respondent had ever exhibited any of the following behaviors by the time of the survey: "had an alcoholic drink," "tried a cigarette," "damaged anything in a public place that didn't belong to [them]," "spray painted on a building," "taken something from a shop without paying for it," "been noisy or rude in public so that people complained" (Cronbach's α =0.52). By wave 5 (modal age 11), 31% of cohort members had engaged in delinquent behavior.

The binary delinquency measure at age 14 included those same measures as well as: "ever smoked cannabis," "been given a formal warning or caution by police," "been stopped and questioned by the police," and "missed school without parents' permission" (Cronbach's α = 0.75). The questions regarding substance use and police contact were asked if the question "ever" applied to the respondent. All other questions at age 14 asked whether the respondent had engaged in the behavior within the "last 12 months." By wave 6 (modal age 14), 58% of cohort members had engaged in some form of delinquency.

Sustained Delinquency

Sustained delinquency was coded as a binary measure based on whether respondents indicated that they had persisted in their delinquency at both the age 11 and 14 waves. All respondents who did not indicate delinquency at both waves were coded as 0. Approximately 22% of cohort members engaged in delinquent behavior by age 11 and 14 years.

Delinquency Variety Score

The variety score of delinquency was coded to represent the summation of positive responses to participation in each of the ten delinquent behaviors at age 14 listed above. The range for the delinquency variety score ranged from 0-10, with a mean of 1.24 delinquent behaviors. Prior research has indicated that binary coding schemes may not be sufficient for assessing delinquent behavior (Sweeten 2012), so the variety score for delinquent behavior should provide a more nuanced picture of delinquent behavior at age 14. Additionally, the variety score helps to account for potential severity of delinquent behavior, rather than treating any participation in delinquent behavior equally.

Low-Self Control

Hyperactivity was measured as part of the Strengths and Difficulties Questionnaire (SDQ) at age 3 (R. Goodman, 2001; www.sdqinfo.com). Items from the hyperactivity scale are used to operationalize low self-control in the MCS cohort. The measure for low self-control includes items of whether the cohort member is “constantly fidgeting,” “easily distracted,” “restless, overactive, or cannot stay still for long,” “thinks things out before acting” (reverse coded), “see tasks through to the end” (reverse coded). Responses to these items range from 0 “not true” to 2 “certainly true.” The SDQ provides a clinical threshold for each of its subscales to indicate thresholds for problematic behaviors (Goodman, Ford, et al. 2000). Scoring a seven or above out of ten on this subscale indicates a clinical level of hyperactivity. This variable was coded to be a binary indicator for whether or not a child reached that clinical threshold at age 3 years.

Conduct Problems

Conduct problems were also measured as part of the SDQ at age 3 through parent's reports. Items from this scale are used to indicate aggressive childhood behaviors. This scale includes items such as "often has temper tantrums," "generally obedient" (reverse coded), "fights with or bullies other children," "often argumentative with adults," and "can be spiteful to others" (Cronbach's $\alpha = 0.68$). Responses to these items range from 0 "not true" to 2 "certainly true." As with the low self-control measure, a clinical threshold of 4 or above was used to code this measure as a binary variable indicating clinical levels of conduct problems at age 3.

Cognitive Abilities

Cognitive abilities were measured at age 3 through the use of the British Ability Scales II (BAS II). The BAS II is a cognitive battery assessing ability and educational achievement (Elliott, Smith, and McCulloch 1996). At age 3 years, the BAS II primarily tests expressive verbal ability. Children are shown a series of pictures and are asked to name the objects depicted. Percentile scores are reported for the MCS children. Percentile scores adjust for the test item difficulty and the cohort member's age, while also indicating relative ability in comparison to the rest of the sample (Connelly 2013).

Prenatal & Perinatal Risk Factors

Based on Moffitt's dual taxonomy theory, all models include controls for several prenatal and perinatal risk factors that could influence future delinquency. Each of these risk factors were reported by the primary caregiver at either wave 1 (modal age 9 months) or wave 2 (modal age 3 years), which in the vast majority of cases is the birth mother. *Low birth weight* is measured as any weight less than 2.5kg, which is the standard threshold (Cutland et al. 2017). Less than 4% of MCS children had low birth weight. *Birth complications* refer to a binary measure for any medical complications that arose during labor, such as “breech birth – feet first” or “foetal distress”. Approximately 31% of caregivers reported complications at birth. *Neurological deficits* refer to a binary measure of whether any central nervous system disorders were diagnosed by age 3, such as “epilepsy,” “convulsions,” or “blackouts.” Less than 5% of the sample reported one of these neurological deficits. *Maternal smoking behavior* is coded as a categorical measure to capture the dynamic changes in smoking behavior around pregnancy. The categories coded were “Never Smoked During Pregnancy,” “Stopped Smoking During Pregnancy,” and “Smoked Throughout Pregnancy.” Approximately 26% of caregivers reported maternal smoking behavior throughout pregnancy, while about 13% reported stopping smoking partway through pregnancy. *Maternal drinking behavior* refers to a binary measure of whether the cohort member’s mother ever drank alcohol during her pregnancy. About 30% of caregivers reported maternal alcohol use during pregnancy.

Sociodemographic Controls

A variety of sociodemographic characteristics were utilized as controls for all analyses. *Parent(s’) highest educational level* is based on the European national vocational qualification (NVQ) scale ranging from NCQ0 to NVQ5. NVQ0 is equivalent to not having a diploma, while NVQ5 is equivalent to postsecondary academic credentials. *Race/ethnicity* is coded as a categorical variable of White British, Black British (“Black or Black British”), Asian British (“Pakistani and Bangladeshi” and “Indian”), and Other British (“Mixed” and “Other Ethnic Group”). White British is used as the reference group for all models. Over 85% of the sample reported their racial/ethnic group as White British. *Age* of the cohort member was measured during either wave 5 (modal age 11 years) or wave 6 (modal age 14 years) and was included as a control in every model. The focal wave for the outcome of interest determined whether wave 5 or wave 6 *age* was used (i.e. wave 5 *age* would be used in a model predicting delinquency at wave 5). Finally, *sex* is present in all models (male=1), either as a control in primary analyses or a moderator in exploratory analyses. Approximately 52% of the sample is male.

Developmental Periods

For the primary analyses, childhood TBI covers ages 3 years to 11 years. The MCS data allow for more fine-grained explorations of the effects of childhood TBI. To explore possible developmental period-specific effects of TBI on delinquent behavior, the same injury categories defined above are split into shorter timeframes. Injuries that occurred from 3 to 5 years, from 5 to 7 years, from 7 to 11 years, and from 11 to 14 years will be used in these exploratory models.

Externalizing Behavior

For supplementary analyses, externalizing behavior will be examined as an outcome following TBI. Externalizing behavior was based on the Hyperactivity and Conduct Problems subscales of the Strengths and Difficulties Questions (SDQ) at ages 11 and 14 (R. Goodman, 2001; *www.sdqinfo.com*). Reports of this behavior were collected from the primary caregiver. Items from these subscales included whether the cohort member is: “constantly fidgeting,” “easily distracted,” “restless, overactive, or cannot stay still for long,” “thinks things out before acting (reverse coded),” “see tasks through to the end (reverse coded)”, “often has temper tantrums,” “generally obedient (reverse coded),” “fights with or bullies other children,” “often lies or cheats,” and “steals from home, school, or elsewhere.” Responses to these items range from 0 “not true” to 2 “certainly true.”

The SDQ has been used to assess clinical levels of behavioral problems in children and adolescents (Goodman et al. 2000; Goodman, Renfrew, and Mullick 2000). Cohort members who scored an 11 or greater on the externalizing behavior scale were coded as having reached a clinical level, which would indicate a greater probability of some antisocial behavior diagnosis (Goodman et al. 2000; Goodman, Renfrew, et al. 2000).

Analytic Strategy

As previously mentioned, the MCS is a longitudinal and nationally representative survey of youth in the UK born at the turn of the century. The population was stratified at both the country level and the electoral ward level. Electoral wards were oversampled to obtain information about disadvantaged youth in the UK. The data were weighted to adjust for non-response bias for the UK as a whole (Plewis, 2007). In all analyses, survey weights, provided by the investigators, were used to account for the complex survey design and sampling procedures by using the “svy” command in Stata 15.

To account for missing data, multiple imputation strategies that relied on chained regressions were used. In order to account for the variety of outcomes and operationalizations of variables, several imputations were carried out. Two sets of chained imputations were performed for the main age 11 and age 14 outcomes. All multiple imputations were run using the “mi estimate” command in Stata 15 (StataCorp 2017). Previous studies have used multiple imputations with the MCS data and retained accurate estimates (Staff et al. 2019).

For the age 11 analytic sample, 25 imputations were run to achieve a final analytic sample of 13,287 cohort members with valid statistical weights. All variables of interest were missing less than 10% of cases, except for two—low self-control and cognitive abilities at age 3 years, which were missing 13.0% and 14.4%, respectively. Delinquency at age 11 was missing on less than 3% of cases, and the injury status variable was only missing on 40 (0.3%) out of the 13,287 cases.

Data were imputed 25 times to achieve an analytic sample of 11,714 cohort members with valid statistical weights for the age 14 analytic sample. Similarly, all variables were missing less than 10% of cases, except for low self-control (12.3%) and cognitive abilities (13.5%) at age 3 years. Delinquency at age 14 was missing on 3.0% of cases, and the injury status variable was missing on 0.4% out of the 11,714 cases. For any model predicting delinquency onset by age 14, those who reported delinquent behavior onset at age 11 are excluded, producing an analytic sample of 8,385.

The analysis will proceed in five primary steps. First, I examine whether early-life risk factors are associated with selection into one of the injury categories. Multinomial logistic regressions are used to compare risk factors associated with NI, OI, and TBI. Second, the relationship between injury status and early-onset delinquency is examined using logistic regressions. Models are run several times, using either NI or OI as the reference category to show how results may vary depending on the foil to TBI. Third, the relationship between injury status and adolescent-typical delinquency onset is examined using logistic regression. Similarly, these models will be tested with varying reference categories. Fourth, logistic regression will be used to examine the relationship between childhood TBI and sustained delinquent behavior. Finally, binomial regression will be used to examine how childhood TBI affects the count of delinquent behaviors exhibited at age 14. All analyses use both survey weights and imputed data.

The outlined approach is relatively standard when looking at binary measures of delinquent behavioral outcomes. However, one major limitation that has been identified is the use of a binary measure of delinquency (Sweeten 2012), as binary measures are not the best indicators of extent of delinquent behavior. The analyses exploring age 14 delinquency as a variety score help alleviate this concern. Since the variety score for delinquent is bounded (max=10), binomial regressions are used, which provide more accurate estimates than traditional regression models for count outcomes (Britt, Rocque, and Zimmerman 2018).

Alternative Specifications

To examine further nuance in the relationship between TBI and delinquency, several additional analyses are conducted. All of the primary models will also be examined when stratified by sex, to examine possible differences between males and females. Developmental period effects are explored through the use of shorter injury timeframes throughout childhood (i.e. TBI from ages 3 to 5 years). Logistic regressions are used for all models, since the outcomes of interest are the binary measures of delinquency at ages 11 and 14 years. Externalizing behavior is explored as an alternative outcome to delinquent behavior. Externalizing behavior is coded as a clinical threshold at ages 11 or 14. These models will also be explored for potential sex differences, as expression of externalizing behavior is likely to differ between males and females. Finally, the alternative coding scheme for TBI (vs nTBI) will be used in a logistic regression predicting delinquent behavior. This model attempts to approximate previous estimates that do not utilize an OI group as a control.

RESULTS

Early Life Factors as Predictors of TBI by Age 11

The results from the multinomial logistic regression examining how early-life risk factors predict injury status by age 11 years are presented in Table 3. Notably, many of the risk factors that are significant in distinguishing TBI from NI are not statistically significant in distinguishing TBI from OI. None of the measures of maternal substance use during pregnancy are predictive of TBI when compared to OI, but they are predictive of TBI when compared to NI. The presence of neurological deficits by age 9 months increases the odds of having TBI, compared to OI, by 47%, after controlling for all other factors (OR = 1.47, 95% CI [1.12, 1.92]). Additionally, reaching the threshold for clinical levels of conduct problems by age 3 years increases the odds of having TBI versus OI by 25% (OR = 1.25, 95% CI [1.07, 1.46]). Being male is also a statistically significant risk factor for TBI, compared to OI (OR = 1.71, 95% CI [1.52, 1.93]). Many of the other demographic factors are not statistically significant risk factors for TBI, instead of OI. However, those who are Asian British have a 37% decrease in the odds of having a TBI, compared to an OI (OR = 0.63, 95% CI [0.47, 0.85]).

Table 3. Multinomial Logistic Regression of Early-Life Risk Factors Predicting Injury Status Category (N=11,714)

	TBI (vs OI)			TBI (vs NI)			NI (vs OI)		
	OR		95% CI	OR		95% CI	OR		95% OI
Early-Life Risk Factors (age 9 months)									
Low Birthweight (<2.5kg)	0.98		[0.73, 1.32]	0.91		[0.65, 1.28]	1.07		[0.77, 1.49]
Birth Complications	0.92		[0.81, 1.03]	1.15		[0.99, 1.32]	0.80	***	[0.70, 0.91]
Neurological Deficits	1.47	**	[1.12, 1.92]	1.78	***	[1.32, 2.40]	0.82		[0.60, 1.12]
Maternal Smoking Behaviors									
Never Smoked During Pregnancy	REF			REF			REF		
Stopped Smoking During Pregnancy	1.04		[0.85, 1.27]	1.22	*	[1.01, 1.47]	0.85		[0.71, 1.02]
Smoked Throughout Pregnancy	0.97		[0.83, 1.13]	1.17		[0.96, 1.42]	0.83	*	[0.70, 0.99]
Maternal Alcohol Use During Pregnancy	0.91		[0.81, 1.04]	0.87	*	[0.76, 0.99]	1.05		[0.93, 1.19]
Clinical Hyperactivity (age 3)	0.91		[0.75, 1.12]	1.14		[0.89, 1.45]	0.80	*	[0.65, 0.99]
Clinical Conduct Problems (age 3)	1.25	**	[1.07, 1.46]	1.46	***	[1.28, 1.68]	0.85	*	[0.76, 0.97]
Cognitive Abilities (age 3)	1.00		[1.00, 1.00]	1.00		[1.00, 1.00]	1.00	*	[0.99, 1.00]
Highest Parental Education	0.98		[0.93, 1.04]	1.05		[1.00, 1.11]	0.94	**	[0.89, 0.98]
Race/Ethnicity (vs White British)									
Asian British	0.63	**	[0.47, 0.85]	0.37	***	[0.27, 0.50]	1.70	***	[1.40, 2.06]
Black British	0.93		[0.63, 1.37]	0.47	***	[0.32, 0.68]	1.99	***	[1.38, 2.86]
Other British	0.99		[0.61, 1.60]	0.45	***	[0.30, 0.67]	2.20	***	[1.56, 3.10]
Age	1.07		[0.94, 1.21]	0.99		[0.86, 1.13]	1.08		[0.96, 1.22]
Male	1.71	***	[1.52, 1.93]	1.83	***	[1.60, 2.10]	0.93		[0.84, 1.04]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Injury Predicting Age 11 Delinquency

Table 4 presents the results from a bivariate logistic regression of injury status predicting delinquency at age 11 years. Model 1 displays the estimated odds ratios for this regression when NI is used as the reference category. The estimates for both OI and TBI are statistically significant, reflecting increased odds by 16% (OR = 1.16, 95% CI [1.04, 1.30]) and 45% (OR = 1.45, 95% CI [1.27, 1.65]), respectively. Model 2 displays this same regression but uses OI as the reference category. History of TBI is still significantly associated with increased odds of delinquency, but the increase is smaller than that of Model 1 (OR = 1.25, 95% CI [1.12, 1.39]).

Table 4. Logistic Regression of Injury Status Category Predicting Delinquency at Age 11 (N=13,287)

	Model 1			Model 2		
	OR		95% CI	OR		95% CI
Injury Status						
No Injury	REF			0.86	*	[0.77, 0.97]
Orthopedic Injury	1.16	*	[1.04, 1.30]	REF		
Traumatic Brain Injury	1.45	***	[1.27, 1.65]	1.25	***	[1.12, 1.39]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 5 displays the estimated odds ratios from the multivariate logistic regression of injury status predicting early-onset delinquency. As before, Model 1 uses NI as a reference category, while Model 2 uses OI. In Model 1, the effect of TBI on early-onset delinquency is statistically significant, net of controls (OR = 1.23, 95% CI [1.08, 1.40]). When using the more conservative test with OI as a reference category, TBI is still significantly associated with early-onset delinquency. A history of TBI increases the odds of being delinquent at age 11 by 14% (OR = 1.14, 95% CI [1.02, 1.27]). Many of the other early-life risk factors are statistically significant as well. Maternal smoking all throughout pregnancy is associated with a 79% increase in the odds of age early-onset delinquency (OR = 1.79, 95% CI [1.57, 2.03]), while maternal alcohol use during pregnancy is associated with a 19% increase (OR = 1.19, 95% CI [1.08, 1.32]). Individuals with low levels of self-control at age 3 are at a 22% increase in the odds of delinquency by age 11 (OR = 1.22, 95% CI [1.05, 1.42]), while those with high levels of conduct problems are at a 31% increase in the odds (OR = 1.31, 95% CI [1.18, 1.45]). Those who identify as Asian British have decreased odds of early-onset delinquency (OR = 0.71, 95% CI [0.58, 0.88]), but no other racial/ethnic group have significant associations with delinquency. Being male increases the odds of early-onset delinquency, compared to females, by 71% (OR = 1.71, 95% CI [1.55, 1.88]).

Table 5. Logistic Regression of Injury Status Category Predicting Delinquency at Age 11 (N=13,287)

	Model 1			Model 2		
	OR		95% CI	OR		95% CI
Injury Status						
No Injury	REF			0.92		[0.82, 1.03]
Orthopedic Injury	1.09		[0.97, 1.22]	REF		
Traumatic Brain Injury	1.23	**	[1.08, 1.40]	1.14	*	[1.02, 1.27]
Early-Life Risk Factors (age 9 months)						
Low Birthweight (<2.5kg)	1.07		[0.83, 1.37]	1.07		[0.83, 1.37]
Birth Complications	1.01		[0.91, 1.11]	1.01		[0.91, 1.11]
Neurological Deficits	0.96		[0.76, 1.21]	0.96		[0.76, 1.21]
Maternal Smoking Behaviors						
Never Smoked During Pregnancy	REF			REF		
Stopped Smoking During Pregnancy	1.29	**	[1.11, 1.50]	1.29	**	[1.11, 1.50]
Smoked Throughout Pregnancy	1.79	***	[1.57, 2.03]	1.79	***	[1.57, 2.03]
Maternal Alcohol Use During Pregnancy	1.19	**	[1.08, 1.32]	1.19	***	[1.08, 1.32]
Clinical Hyperactivity (age 3)	1.22	**	[1.05, 1.42]	1.22	**	[1.05, 1.42]
Clinical Conduct Problems (age 3)	1.31	***	[1.18, 1.45]	1.31	***	[1.18, 1.45]
Cognitive Abilities (age 3)	1.00		[1.00, 1.00]	1.00		[0.99, 1.00]
Highest Parental Education	0.94	**	[0.91, 0.98]	0.94	**	[0.91, 0.98]
Race/Ethnicity (vs White British)						
Asian British	0.71	**	[0.58, 0.88]	0.71	**	[0.58, 0.88]
Black British	1.22		[0.90, 1.66]	1.22		[0.90, 1.66]
Other British	0.88		[0.67, 1.15]	0.88		[0.67, 1.15]
Age	1.06		[0.96, 1.16]	1.06		[0.96, 1.17]
Male	1.71	***	[1.55, 1.88]	1.71	***	[1.55, 1.88]

*p < 0.05; **p < 0.01; ***p < 0.001

Injury Predicting Age 14 Delinquency

Next, the results from a bivariate logistic regression of injury status on delinquency at age 14 are displayed in Table 6. The sample size is reduced to 8,385 cases, because the model excludes those who have already reported delinquency onset by age 11. In Model 1, both OI and TBI are significantly associated with increased odds of delinquency at age 11, when compared to NI (OI: OR = 1.21, 95% CI [1.06, 1.40]; TBI: OR = 1.38, 95% CI [1.17, 1.63]). When compared to OI in Model 2, TBI is no longer significantly associated with an increase in the odds of adolescent delinquency (OR = 1.14, 95% CI [0.96, 1.32]).

Table 6. Bivariate Logistic Regression of Injury Status Category Predicting Delinquency at Age 14 (N=8,385)

	Model 1			Model 2		
	OR		95% CI	OR		95% CI
Injury Status						
No Injury	REF			0.82	**	[0.72, 0.95]
Orthopedic Injury	1.21	**	[1.06, 1.40]	REF		
Traumatic Brain Injury	1.38	***	[1.17, 1.63]	1.14		[0.96, 1.32]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 7 displays the results from the multivariate logistic regression of injury status predicting adolescent delinquency. Similar to previous regressions, Model 1 uses NI as a reference group, while Model 2 uses OI. In Model 1, TBI is a significant predictor of adolescent delinquency, compared to NI and net of all other factors, and is associated with a 21% increase in the odds of delinquent behavior (OR = 1.21, 95% CI [1.01, 1.43]). However, when using OI as a more conservative reference group, the estimated effect of TBI is both attenuated and no longer statistically significant (OR = 1.12, 95% CI [0.96, 1.30]).

None of the other early-life risk factors are significantly associated with adolescent delinquency. Low birthweight and neurological deficits trend toward being protective against adolescent delinquency, but neither reaches the level of statistical significance. Unsurprisingly, all of the maternal substance use measures are significantly associated with increased odds of adolescent delinquency. Maternal smoking during pregnancy is associated with either a 74% (OR = 1.74, 95% CI [1.43, 2.12]) or a 70% (OR = 1.70, 95% CI [1.44, 2.02]) increase in the odds of adolescent delinquency, depending on whether the maternal smoking occurred throughout the duration of pregnancy. Compared to those who are White British, all of the racial/ethnic groups are protective against adolescent delinquency (Asian British: OR = 0.34, 95% CI [0.25, 0.45]; Black British: OR = 0.56, 95% CI [0.36, 0.87]; Other British: OR = 0.60, 95% CI [0.41, 0.89]). Those who are slightly older at the time of the survey are at a 43% increased risk of adolescent delinquency (OR = 1.43, 95% CI [1.25, 1.63]). Estimates indicate that males have about a 12% higher likelihood of being delinquent by age 14 (OR: 1.12, 95% CI [1.00, 1.27). This estimate does not reach conventional levels of statistical significance, but only barely (p<0.06).

Injury Predicting Sustained Delinquency

Table 8 displays the results from a logistic regression of injury status on sustained delinquent behavior from age 11 to age 14 years. For this model, OI is used as a reference group to obtain the most accurate and conservative estimates. Even when compared to OI, a history of TBI is significantly associated with a 20% increase in the odds of sustained delinquent behavior over time (OR = 1.20, 95% CI [1.03, 1.39]). Although some of the early-life risk factors, such as low birthweight and neurological deficits, display slight protective effects, none reach statistical significance. Both maternal smoking throughout pregnancy (OR = 2.02, 95% CI [1.71, 2.38]) and maternal alcohol use during pregnancy (OR = 1.19, 95% CI [1.03, 1.37]) are significantly associated with sustained delinquent behavior over time. Males have 54% increased odds of sustained delinquency, compared to females (OR = 1.54, 95% CI [1.35, 1.75]).

Table 7. Logistic Regression of Injury Status Category Predicting Delinquency at Age 14 (N=8,385)

	Model 1			Model 2		
	OR		95% CI	OR		95% CI
Injury Status						
No Injury	REF			0.93		[0.80, 1.07]
Orthopedic Injury	1.08		[0.93, 1.24]	REF		
Traumatic Brain Injury	1.21	*	[1.01, 1.43]	1.12		[0.96, 1.30]
Early-Life Risk Factors (age 9 months)						
Low Birthweight (<2.5kg)	0.76		[0.54, 1.09]	0.76		[0.54, 1.09]
Birth Complications	1.00		[0.88, 1.14]	1.00		[0.88, 1.14]
Neurological Deficits	0.76		[0.54, 1.07]	0.76		[0.54, 1.07]
Maternal Smoking Behaviors						
Never Smoked During Pregnancy	REF			REF		
Stopped Smoking During Pregnancy	1.74	***	[1.43, 2.12]	1.74	***	[1.43, 2.12]
Smoked Throughout Pregnancy	1.70	***	[1.43, 2.02]	1.70	***	[1.43, 2.02]
Maternal Alcohol Use During Pregnancy	1.17	*	[1.03, 1.34]	1.17	*	[1.03, 1.34]
Clinical Hyperactivity (age 3)	1.08		[0.85, 1.37]	1.08		[0.85, 1.37]
Clinical Conduct Problems (age 3)	1.16	*	[1.00, 1.34]	1.16	*	[1.00, 1.34]
Cognitive Abilities (age 3)	1.00		[1.00, 1.00]	1.00		[1.00, 1.00]
Highest Parental Education	0.99		[0.95, 1.04]	0.99		[0.95, 1.04]
Race/Ethnicity (vs White British)						
Asian British	0.34	***	[0.25, 0.45]	0.34	***	[0.25, 0.45]
Black British	0.56	*	[0.36, 0.87]	0.56	*	[0.36, 0.87]
Other British	0.60	*	[0.41, 0.89]	0.60	*	[0.41, 0.89]
Age	1.43	***	[1.25, 1.63]	1.43	***	[1.25, 1.63]
Male	1.12		[1.00, 1.27]	1.12		[1.00, 1.27]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 8. Logistic Regression of Injury Status Category Predicting Sustained Delinquency at Age 11 and 14 (N=11,714)

	OR		95% CI
Injury Status			
No Injury	0.95		[0.81, 1.11]
Orthopedic Injury	REF		
Traumatic Brain Injury	1.20	*	[1.03, 1.39]
Early-Life Risk Factors (age 9 months)			
Low Birthweight (<2.5kg)	0.81		[0.57, 1.16]
Birth Complications	0.98		[0.86, 1.11]
Neurological Deficits	0.81		[0.62, 1.07]
Maternal Smoking Behaviors			
Never Smoked During Pregnancy	REF		
Stopped Smoking During Pregnancy	1.32	**	[1.08, 1.61]
Smoked Throughout Pregnancy	2.02	***	[1.71, 2.38]
Maternal Alcohol Use During Pregnancy	1.19	*	[1.03, 1.37]
Clinical Hyperactivity (age 3)	1.18		[0.98, 1.42]
Clinical Conduct Problems (age 3)	1.19	*	[1.04, 1.37]
Cognitive Abilities (age 3)	1.00		[1.00, 1.00]
Highest Parental Education	0.96		[0.91, 1.01]
Race/Ethnicity (vs White British)			
Asian British	0.47	***	[0.35, 0.63]
Black British	0.86		[0.55, 1.34]
Other British	0.40	***	[0.24, 0.69]
Age	1.02		[0.88, 1.19]
Male	1.54	***	[1.35, 1.75]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Injury Predicting Delinquency Variety

Table 9 presents the estimates from a binomial regression of injury status on variety of delinquent behaviors exhibited at age 14 years. When compared to OI, a history of TBI is significantly and positively associated with variety of delinquency behavior. Specifically, those who have a TBI have a 9% increase in the odds of committing an additional delinquent behavior than those who have OI, net of other controls (OR = 1.09, 95% CI [1.00, 1.19]). Neurological deficits early in life are significantly associated with a decrease in the odds of exhibiting additional delinquent behaviors (OR = 0.77, 95% CI [0.63, 0.93]). Maternal smoking throughout the duration of pregnancy is associated with an 80% increase in the odds of additional delinquent behaviors at age 14 (OR = 1.80, 95% CI [1.63, 1.98]), but the effect of maternal alcohol use during pregnancy is not statistically significant. The estimates regarding race/ethnicity and sex follow similar patterns to previous models, with non-White British groups and females displaying decreased odds of greater variety in delinquent behavior.

Table 9. Binomial Regression of Injury Status Category Predicting Variety of Delinquent Behavior at Age 14 (N=11,714)

	OR		95% CI
Injury Status			
No Injury	0.92		[0.84, 1.01]
Orthopedic Injury	REF		
Traumatic Brain Injury	1.09	*	[1.00, 1.19]
Early-Life Risk Factors (age 9 months)			
Low Birthweight (<2.5kg)	0.86		[0.70, 1.05]
Birth Complications	0.98		[0.90, 1.06
Neurological Deficits	0.77	**	[0.63, 0.93]
Maternal Smoking Behaviors			
Never Smoked During Pregnancy	REF		
Stopped Smoking During Pregnancy	1.44	***	[1.29, 1.61]
Smoked Throughout Pregnancy	1.80	***	[1.63, 1.98]
Maternal Alcohol Use During Pregnancy	1.06		[0.97, 1.15]
Clinical Hyperactivity (age 3)	1.03		[0.91, 1.16]
Clinical Conduct Problems (age 3)	1.19	***	[1.09, 1.30]
Cognitive Abilities (age 3)	1.00		[1.00, 1.00]
Highest Parental Education	0.99		[0.96, 1.03]
Race/Ethnicity (vs White British)			
Asian British (vs White British)	0.46	***	[0.38, 0.56]
Black British (vs White British)	0.72	*	[0.54, 0.94]
Other British (vs White British)	0.68	*	[0.51, 0.91]
Age	1.26	***	[1.17, 1.37]
Male	1.08	*	[1.01, 1.17]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Alternative Model Specifications

Given the relative lack of research on childhood TBI and its association with later delinquency, the present study aims to explore possible nuances in this relationship. All of the primary models are re-examined when stratified by sex to explore possible sex differences. Additionally, since age at the time of injury may be linked to the severity of deficits, developmental period effects are analyzed. Externalizing behavior is examined as an outcome to check for robustness of findings from the primary models. Finally, an alternative coding scheme for head injury is used to expand on how estimates may differ depending on reference group.

Sex Differences

Table 10 displays the results from multinomial regressions of early-life risk factors predicting injury status. Several notable differences arise in what risk factors are significant predictors of injury. For males, neurological deficits in childhood are significantly predictive of having a TBI, compared to both OI and NI. For females, those neurological deficits are significantly predictive of TBI, compared to NI, but fail to reach levels of statistical significance when compared to OI. Similarly, conduct problems at age 3 are significant risk factors for TBI in both sexes when compared to NI. However, conduct problems are only significant predictors of TBI, compared to OI, for males. Interestingly, being Asian British, compared to White British, is protective against TBI and OI for both sexes, regardless of comparison group.

Table 11 presents the results from a logistic regression of injury status predicting early-onset delinquent behavior. Although estimates tend toward their expected effects, TBI is not a statistically significant predictor of early-onset delinquent for either males or females, when compared to the OI group.

The results from a logistic regression predicting age 14 delinquency are displayed in Table 12. When compared to OI, TBI is not a significant predictor of delinquency for either sex. While the estimates may differ, many of the other risk factors in the model are statistically significant for both sexes, such as maternal nicotine use and age.

Table 10. Logistic Regression of Early-Life Risk Factors Predicting Injury Status Category by Sex (N=11,714)

	TBI (vs OI)						TBI (vs NI)						NI (vs OI)					
	Males			Females			Males			Females			Males			Females		
	OR		95% CI	OR		95% CI	OR		95% CI	OR		95% CI	OR		95% CI	OR		95% CI
Early-Life Risk Factors (age 9 months)																		
Low Birthweight (<2.5kg)	0.81		[0.53, 1.22]	1.22		[0.79, 1.87]	0.80		[0.48, 1.31]	1.07		[0.65, 1.75]	1.01		[0.64, 1.60]	1.14		[0.72, 1.81]
Birth Complications	0.88		[0.75, 1.04]	0.95		[0.80, 1.14]	1.16		[0.96, 1.41]	1.13		[0.91, 1.40]	0.76	**	[0.63, 0.92]	0.84	*	[0.71, 1.00]
Neurological Deficits	1.54	*	[1.07, 2.20]	1.38		[0.93, 2.05]	1.79	*	[1.15, 2.80]	1.76	*	[1.13, 2.75]	0.86		[0.52, 1.41]	0.79		[0.52, 1.19]
Maternal Smoking Behaviors																		
Never Smoked During Pregnancy	REF			REF			REF			REF			REF			REF		
Stopped Smoking During Pregnancy	0.90		[0.70, 1.16]	1.21		[0.91, 1.61]	1.21		[0.91, 1.61]	1.26		[0.96, 1.65]	0.75	*	[0.57, 0.98]	0.96		[0.75, 1.24]
Smoked Throughout Pregnancy	0.97		[0.79, 1.20]	0.95		[0.75, 1.21]	1.17		[0.90, 1.52]	1.15		[0.88, 1.51]	0.83		[0.66, 1.05]	0.82		[0.65, 1.05]
Maternal Alcohol Use During Pregnancy	0.85		[0.71, 1.02]	1.01		[0.83, 1.22]	0.86		[0.72, 1.03]	0.90		[0.73, 1.10]	0.99		[0.82, 1.19]	1.12		[0.94, 1.34]
Clinical Hyperactivity (age 3)	0.88		[0.68, 1.14]	0.93		[0.68, 1.28]	1.16		[0.85, 1.57]	1.1		[0.78, 1.57]	0.76		[0.58, 1.01]	0.85		[0.61, 1.17]
Clinical Conduct Problems (age 3)	1.37	***	[1.14, 1.65]	1.10		[0.89, 1.36]	1.55	***	[1.28, 1.88]	1.32	*	[1.06, 1.65]	0.88		[0.74, 1.05]	0.83	*	[0.70, 1.00]
Cognitive Abilities (age 3)	1.00		[0.99, 1.00]	1.00		[1.00, 1.00]	1.00		[1.00, 1.00]	1		[1.00, 1.00]	1.00		[0.99, 1.00]	1.00		[0.99, 1.00]
Highest Parental Education	0.97		[0.91, 1.04]	0.99		[1.00, 1.00]	1.07	*	[1.00, 1.15]	1.03		[0.96, 1.10]	0.90	**	[0.84, 0.97]	0.96		[0.91, 1.03]
Race/Ethnicity (vs White British)																		
Asian British	0.63	*	[0.40, 0.98]	0.58	**	[0.40, 0.83]	0.47	**	[0.31, 0.72]	0.27	***	[0.19, 0.38]	1.34		[0.97, 1.84]	2.14	***	[1.62, 2.93]
Black British	0.81		[0.48, 1.36]	1.09		[0.66, 1.79]	0.53	*	[0.30, 0.93]	0.42	***	[0.26, 0.66]	1.54		[0.88, 2.68]	2.62	***	[1.61, 4.25]
Other British	1.12		[0.61, 2.08]	0.73		[0.39, 1.37]	0.55		[0.30, 1.01]	0.31	***	[0.17, 0.55]	2.03	***	[1.35, 3.05]	2.39	***	[1.48, 3.85]
Age	1.02		[0.85, 1.21]	1.13		[0.93, 1.37]	0.95		[0.79, 1.13]	1.04		[0.84, 1.29]	1.07		[0.91, 1.26]	1.09		[0.91, 1.30]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 11. Logistic Regression of Injury Status Category Predicting Delinquency at Age 11 by Sex (N=13,287)

	Males N = 6,712			Females N = 6,575		
	OR		95% CI	OR		95% CI
Injury Status						
No Injury	0.92		[0.79, 1.09]	0.91		[0.77, 1.07]
Orthopedic Injury	REF			REF		
Traumatic Brain Injury	1.13		[1.08, 1.40]	1.14		[0.94, 1.38]
Early-Life Risk Factors (age 9 months)						
Low Birthweight (<2.5kg)	1.07		[0.83, 1.37]	1.07		[0.75, 1.52]
Birth Complications	1.00		[0.91, 1.11]	1.01		[0.87, 1.18]
Neurological Deficits	0.93		[0.76, 1.21]	0.99		[0.71, 1.38]
Maternal Smoking Behaviors						
Never Smoked During Pregnancy	REF			REF		
Stopped Smoking During Pregnancy	1.28	*	[1.11, 1.50]	1.31	*	[1.06, 1.63]
Smoked Throughout Pregnancy	1.74	***	[1.57, 2.03]	1.85	***	[1.52, 2.24]
Maternal Alcohol Use During Pregnancy	1.25	**	[1.08, 1.32]	1.11		[0.94, 1.32]
Clinical Hyperactivity (age 3)	1.27	*	[1.05, 1.42]	1.14		[0.89, 1.47]
Clinical Conduct Problems (age 3)	1.34	***	[1.18, 1.45]	1.27		[1.07, 1.51]
Cognitive Abilities (age 3)	1.00		[1.00, 1.00]	1.00		[1.00, 1.00]
Highest Parental Education	0.95	*	[0.91, 0.98]	0.93	*	[0.88, 0.99]
Race/Ethnicity (vs White British)						
Asian British	0.78		[0.58, 0.88]	0.63	**	[0.46, 0.87]
Black British	0.95		[0.90, 1.66]	1.72	**	[1.18, 2.52]
Other British	0.82		[0.67, 1.15]	0.97		[0.68, 1.39]
Age	1.02		[0.96, 1.16]	1.10		[0.95, 1.26]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 12. Logistic Regression of Injury Status Category Predicting Delinquency at Age 14 by Sex (N=8,385)

	Males N = 3,857			Females N = 4,528		
	OR		95% CI	OR		95% CI
Injury Status						
No Injury	0.90		[0.72, 1.13]	0.97		[0.81, 1.15]
Orthopedic Injury	REF			REF		
Traumatic Brain Injury	1.12		[0.90, 1.40]	1.09		[0.89, 1.34]
Early-Life Risk Factors (age 9 months)						
Low Birthweight (<2.5kg)	0.75		[0.47, 1.20]	0.78		[0.47, 1.29]
Birth Complications	0.95		[0.78, 1.16]	1.04		[0.87, 1.26]
Neurological Deficits	0.84		[0.51, 1.38]	0.69		[0.43, 1.10]
Maternal Smoking Behaviors						
Never Smoked During Pregnancy	REF			REF		
Stopped Smoking During Pregnancy	1.60	**	[1.17, 2.20]	1.85	***	[1.45, 2.36]
Smoked Throughout Pregnancy	1.70	***	[1.33, 2.17]	1.71	***	[1.35, 2.18]
Maternal Alcohol Use During Pregnancy	1.20		[0.98, 1.45]	1.16		[0.97, 1.39]
Clinical Hyperactivity (age 3)	1.01		[0.74, 1.39]	1.18		[0.84, 1.64]
Clinical Conduct Problems (age 3)	1.28	*	[1.02, 1.59]	1.05		[0.86, 1.28]
Cognitive Abilities (age 3)	1.00		[1.00, 1.01]	1.00		[1.00, 1.00]
Highest Parental Education	1.02		[0.94, 1.10]	0.99		[0.93, 1.06]
Race/Ethnicity (vs White British)						
Asian British	0.49	***	[0.34, 0.71]	0.21	***	[0.12, 0.32]
Black British	0.64		[0.33, 1.23]	0.47	**	[0.29, 0.75]
Other British	0.73		[0.42, 1.27]	0.49	**	[0.28, 0.84]
Age	1.38	**	[1.14, 1.66]	1.46	***	[1.22, 1.75]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 13 displays the logistic regression of injury status predicting sustained delinquent behavior from age 11 to age 14. Once again, estimates suggest that TBI may be a risk factor for sustained delinquency but do not reach levels of statistical significance.

Table 14 presents the results of binomial regressions predicting variety of delinquent behaviors exhibited by age 14. For males, a history of TBI is a significant predictor of engaging

Table 13. Logistic Regression of Injury Status Category Predicting Sustained Delinquency at Age 11 and 14 by Sex (N=11,714)

	Males N = 5,877			Females N = 5,837		
	OR		95% CI	OR		95% CI
Injury Status						
No Injury	0.95		[0.76, 1.18]	0.97		[0.76, 1.23]
Orthopedic Injury	REF			REF		
Traumatic Brain Injury	1.21		[0.99, 1.48]	1.19		[0.94, 1.51]
Early-Life Risk Factors (age 9 months)						
Low Birthweight (<2.5kg)	0.85		[0.52, 1.36]	0.78		[0.46, 1.35]
Birth Complications	1.01		[0.85, 1.20]	0.93		[0.77, 1.13]
Neurological Deficits	0.89		[0.62, 1.30]	0.69		[0.43, 1.10]
Maternal Smoking Behaviors						
Never Smoked During Pregnancy	REF			REF		
Stopped Smoking During Pregnancy	1.34	*	[1.03, 1.75]	1.30		[0.97, 1.76]
Smoked Throughout Pregnancy	1.86	***	[1.49, 2.32]	2.24	***	[1.75, 2.88]
Maternal Alcohol Use During Pregnancy	1.35	**	[1.13, 1.62]	0.98		[0.78, 1.23]
Clinical Hyperactivity (age 3)	1.21		[0.95, 1.54]	1.13		[0.80, 1.60]
Clinical Conduct Problems (age 3)	1.20		[0.99, 1.46]	1.18		[0.93, 1.49]
Cognitive Abilities (age 3)	1.00		[1.00, 1.00]	1.00		[1.00, 1.00]
Highest Parental Education	0.99		[0.93, 1.06]	0.92		[0.84, 1.00]
Race/Ethnicity (vs White British)						
Asian British	0.51	***	[0.35, 0.74]	0.41	***	[0.25, 0.69]
Black British	0.79		[0.46, 1.33]	0.97		[0.50, 1.89]
Other British	0.39	*	[0.19, 0.80]	0.43	*	[0.22, 0.87]
Age	1.03		[0.86, 1.24]	1.02		[0.82, 1.27]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

in a great variety of delinquent behaviors (OR = 1.15, 95% CI [1.02, 1.29]). For females, TBI is not a significant predictor, but cohort members reporting no injuries have a decreased likelihood of committing additional delinquent behaviors (OR = 0.88, 95% CI [0.77, 1.00]). Many of the other risk factors, such as maternal substance use during pregnancy, are significant and predictive of greater delinquent involvement for both sexes.

Table 14. Binomial Regression of Injury Status Category Predicting Variety of Delinquent Behavior at Age 14 by Sex (N=11,714)

	Males N = 5,877			Females N = 5,377		
	OR		95% CI	OR		95% CI
Injury Status						
No Injury	0.97		[0.85, 1.11]	0.88	*	[0.77, 1.00]
Orthopedic Injury	REF			REF		
Traumatic Brain Injury	1.15	*	[1.02, 1.29]	1.03		[0.90, 1.18]
Early-Life Risk Factors (age 9 months)						
Low Birthweight (<2.5kg)	0.88		[0.66, 1.18]	0.83		[0.62, 1.11]
Birth Complications	0.95		[0.85, 1.07]	1.00		[0.88, 1.13]
Neurological Deficits	0.79		[0.62, 1.01]	0.73		[0.52, 1.01]
Maternal Smoking Behaviors						
Never Smoked During Pregnancy	REF			REF		
Stopped Smoking During Pregnancy	1.34	***	[1.16, 1.54]	1.57	***	[1.34, 1.84]
Smoked Throughout Pregnancy	1.67	***	[1.47, 1.91]	1.95	***	[1.71, 2.22]
Maternal Alcohol Use During Pregnancy	1.08		[0.97, 1.21]	1.03		[0.91, 1.16]
Clinical Hyperactivity (age 3)	1.04		[0.89, 1.21]	1.02		[0.84, 1.22]
Clinical Conduct Problems (age 3)	1.28	***	[1.13, 1.45]	1.08		[0.96, 1.22]
Cognitive Abilities (age 3)	1.00		[1.00, 1.00]	1.00		[1.00, 1.00]
Highest Parental Education	1.01		[0.97, 1.05]	0.98		[0.93, 1.03]
Race/Ethnicity (vs White British)						
Asian British	0.57	***	[0.44, 0.73]	0.33	***	[0.24, 0.46]
Black British	0.73		[0.52, 1.03]	0.69		[0.46, 1.05]
Other British	0.75		[0.51, 1.10]	0.60	*	[0.39, 0.91]
Age	1.27	***	[1.14, 1.41]	1.26	***	[1.11, 1.43]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Developmental Periods

Table 15 displays descriptive statistics of injury status for each of the developmental periods of interest. The developmental period represents individuals who reported an injury during that timeframe. From ages 3-5 years, 9.5% of parents reported their child had a TBI. The trend of TBI occurrence follows expected trends, since TBI is more common in younger children (Crowe 2008). Prevalence of OI generally increases across the developmental periods, as children are likely to be more independent and be more active.

Table 15. Weighted Descriptive Statistics of Injury Status Category at Each Developmental Period (N=11,714)

	Ages 3-5	Ages 5-7	Ages 7-11	Ages 11-14
No Injury	71.9%	75.6%	63.7%	64.4%
Orthopedic Injury	18.6%	16.5%	29.7%	30.6%
Traumatic Brain Injury	9.5%	7.9%	6.7%	5.0%

Tables 16, 17, and 18 display logistic regressions for injury status at each of the developmental periods of interest predicting a binary measure of delinquency at either age 11 or age 14. For all tables, Model 1 and Model 3 display the results of bivariate regressions. Model 2 and Model 4 include all early-life controls, but they are not shown to reduce redundancy. Only main effects are shown.

In Table 16, TBI from ages 3-5 years is a significant predictor of early-onset delinquency, even when controlling for all relevant early-life risk factors (OR = 1.31, 95% CI [1.05, 1.64]). However, TBI during this age range is not a significant predictor of delinquency at age 14. The results in Table 17 indicate that TBI from ages 5-7 years is a significant predictor of age 11 delinquency (OR = 1.35, 95% CI [1.05, 1.74]), but this effect is attenuated to non-significance when other controls are added to the model. TBI during this time is not a significant predictor of age 14 delinquency. The results in Table 18 mirror this pattern. TBI from ages 7-11 years is a significant predictor of early-onset delinquency (OR = 1.29, 95% CI [1.01, 1.66]), but this effect is non-significant when other controls are accounted for. Reporting NI during this time is significantly associated with decreased odds of delinquency at both age 11 (OR = 0.86, 95% CI [0.76, 0.97]) and age 14 (OR = 0.82, 95% CI [0.70, 0.95]), even when controlling for other early-life risk factors.

Table 19 displays the results of logistic regressions of injury status from age 11-14 predicting delinquency at age 14. Model 1 displays the results of a bivariate model. TBI is not significantly associated with an increase in the odds of delinquent behavior by age 14 for those who had not been delinquent at age 11. When other early-life risk factors are included in Model 2, this effect remains non-significant; however, both estimates still trend in the expected direction. Model 3 includes a control for delinquent behavior at age 11. Although the estimate for this risk factor is large (OR = 2.51, 95% CI [2.19, 2.87]), its inclusion in the model does not attenuate the estimate for TBI or NI, compared to Model 2. In fact, the estimate for TBI is larger—although still not statistically significant—but this could be due to the larger sample size, which includes those who were delinquent at age 11.

Table 16. Logistic Regressions of Injury Status Category from Ages 3 to 5 Predicting Delinquency

	Age 11 Delinquency (N=13,287)						Age 14 Delinquency (N=8,385)					
	Model 1			Model 2†			Model 3			Model 4†		
	OR		95% CI	OR		95% CI	OR		95% CI	OR		95% CI
Injury Status												
No Injury	0.95		[0.82, 1.09]	1.01		[0.87, 1.17]	0.86		[0.73, 1.02]	0.92		[0.77, 1.10]
Orthopedic Injury	REF			REF			REF			REF		
Traumatic Brain Injury	1.37	**	[1.11, 1.70]	1.31	*	[1.05, 1.64]	0.91		[0.71, 1.16]	0.87		[0.67, 1.14]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

† Models include controls, but estimates are not presented

Table 17. Logistic Regressions of Injury Status Category from Ages 5 to 7 Predicting Delinquency

	Age 11 Delinquency (N=13,287)						Age 14 Delinquency (N=8,385)					
	Model 1			Model 2†			Model 3			Model 4†		
	OR		95% CI	OR		95% CI	OR		95% CI	OR		95% CI
Injury Status												
No Injury	0.82	*	[0.70, 0.96]	0.86		[0.73, 1.01]	0.80	*	[0.67, 0.95]	0.85		[0.71, 1.02]
Orthopedic Injury	REF			REF			REF			REF		
Traumatic Brain Injury	1.35	*	[1.05, 1.74]	1.24		[0.95, 1.61]	0.92		[0.68, 1.25]	0.91		[0.67, 1.23]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

† Models include controls, but estimates are not presented

Table 18. Logistic Regressions of Injury Status Category from Ages 7 to 11 Predicting Delinquency

	Age 11 Delinquency (N=13,287)						Age 14 Delinquency (N=8,385)					
	Model 1			Model 2†			Model 3			Model 4†		
	OR		95% CI	OR		95% CI	OR		95% CI	OR		95% CI
Injury Status												
No Injury	0.81	***	[0.72, 0.92]	0.86	*	[0.76, 0.97]	0.74	***	[0.63, 0.86]	0.82	*	[0.70, 0.95]
Orthopedic Injury	REF			REF			REF			REF		
Traumatic Brain Injury	1.29	*	[1.01, 1.66]	1.22		[0.96, 1.55]	1.00		[0.71, 1.39]	1.04		[0.72, 1.50]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

† Models include controls, but estimates are not presented

Table 19. Logistic Regressions of Injury Status Category from Ages 11 to 14 Predicting Delinquency

	Age 14 Delinquency								
	Model 1 N=8,385			Model 2† N=8,385			Model 3† N=11,714		
	OR		95% CI	OR		95% CI	OR		95% CI
Injury Status									
No Injury	0.69	***	[0.61, 0.79]	0.78	***	[0.68, 0.89]	0.76	***	[0.68, 0.86]
Orthopedic Injury	REF			REF			REF		
Traumatic Brain Injury	1.13		[0.81, 1.59]	1.11		[0.79, 1.56]	1.23		[0.93, 1.61]
Delinquency (age 11)							2.51	***	[2.19, 2.87]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

† Models include controls, but estimates are not presented

Externalizing Behavior

Table 20 presents the results from logistic regression predicting externalizing behavior at age 11 years. Model 1 displays the results for the full sample. Compared to OI, TBI is significantly associated with a 41% increase in the odds of reaching the clinical threshold of externalizing behavior (OR = 1.41, 95% CI [1.16, 1.72]). Model 2 shows the results for males only, and the estimate for TBI is similar to that of the full sample (OR = 1.42, 95% CI [1.13, 1.80]). Model 3 displays the results for females only. The estimates for TBI are still trend toward an increase in the odds of externalizing behavior but is not statistically significant.

The results of logistic regressions predicting clinical externalizing behavior at age 14 years are shown in Table 21. Model 1 displays the results of a bivariate logistic regression. Compared to OI, TBI is significantly associated with a 39% increase in the odds of reaching clinical levels of externalizing behavior at age 14 (OR = 1.39, 95% CI [1.11, 1.73]). Model 2 accounts for all the relevant early-life and sociodemographic controls. With the addition of these controls, the effect of TBI is attenuated and no longer statistically significant.

Table 20. Logistic Regressions of Injury Status Category Predicting Clinical Levels of Externalizing Behavior at Age 11

	Model 1 Full (N = 13,287)			Model 2 Males (N = 6,712)			Model 3 Females (N = 6,575)		
	OR		95% CI	OR		95% CI	OR		95% CI
Injury Status									
No Injury	0.96		[0.78, 1.18]	0.78		[0.60, 1.01]	1.30		[0.93, 1.81]
Orthopedic Injury	REF			REF			REF		
Traumatic Brain Injury	1.41	***	[1.16, 1.72]	1.42	**	[1.13, 1.80]	1.27		[0.87, 1.87]
Early-Life Risk Factors (age 9 months)									
Low Birthweight (<2.5kg)	1.07		[0.70, 1.65]	1.08		[0.67, 1.75]	1.06		[0.48, 2.34]
Birth Complications	1.04		[0.85, 1.27]	1.06		[0.83, 1.36]	0.98		[0.72, 1.35]
Neurological Deficits	1.51	*	[1.03, 2.21]	1.43		[0.88, 2.32]	1.68		[0.90, 3.14]
Maternal Smoking Behaviors									
Never Smoked During Pregnancy	REF			REF			REF		
Stopped Smoking During Pregnancy	1.11		[0.84, 1.47]	1.23		[0.88, 1.74]	0.90		[0.57, 1.42]
Smoked Throughout Pregnancy	1.65	***	[1.33, 2.06]	1.69	***	[1.30, 2.21]	1.61	*	[1.12, 2.31]
Maternal Alcohol Use During Pregnancy	1.01		[0.82, 1.24]	1.12		[0.87, 1.44]	0.80		[0.54, 1.17]
Clinical Hyperactivity (age 3)	2.70	***	[2.15, 3.40]	2.85	***	[2.17, 3.74]	2.48	***	[1.66, 3.71]
Clinical Conduct Problems (age 3)	2.00	***	[1.64, 2.44]	1.97	***	[1.56, 2.49]	2.08	***	[1.53, 2.83]
Cognitive Abilities (age 3)	0.99	***	[0.99, 1.00]	0.99	***	[0.99, 1.00]	0.99	**	[0.98, 1.00]
Highest Parental Education	0.84	***	[0.78, 0.91]	0.83	***	[0.75, 0.91]	0.87	*	[0.78, 0.98]
Race/Ethnicity (vs White British)									
Asian British	0.65	*	[0.46, 0.93]	0.63		[0.40, 1.00]	0.67		[0.36, 1.25]
Black British	0.67		[0.33, 1.40]	0.82		[0.36, 1.89]	0.37		[0.10, 1.34]
Other British	1.09		[0.73, 1.63]	0.89		[0.57, 1.42]	1.40		[0.70, 2.78]
Age	0.77	**	[0.64, 0.93]	0.76	*	[0.60, 0.95]	0.78		[0.60, 1.07]
Male	1.94	***	[1.63, 2.30]						

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

Table 21. Logistic Regressions of Injury Status Category Predicting Clinical Levels of Externalizing Behavior at Age 14 (N=11,714)

	Model 1			Model 2		
	OR		95% CI	OR		95% CI
Injury Status						
No Injury	0.93		[0.75, 1.16]	1.00		[0.80, 1.25]
Orthopedic Injury	REF			REF		
Traumatic Brain Injury	1.39	**	[1.11, 1.73]	1.17		[0.93, 1.48]
Early-Life Risk Factors (age 9 months)						
Low Birthweight (<2.5kg)				0.99		[0.60, 1.62]
Birth Complications				0.87		[0.69, 1.10]
Neurological Deficits				1.33		[0.82, 2.15]
Maternal Smoking Behaviors						
Never Smoked During Pregnancy				REF		
Stopped Smoking During Pregnancy				1.20		[0.87, 1.67]
Smoked Throughout Pregnancy				2.23	***	[1.79, 2.78]
Maternal Alcohol Use During Pregnancy				1.06		[0.85, 1.33]
Clinical Hyperactivity (age 3)				2.29	***	[1.73, 3.03]
Clinical Conduct Problems (age 3)				1.82	***	[1.45, 2.29]
Cognitive Abilities (age 3)				0.99	**	[0.99, 1.00]
Highest Parental Education				0.85	***	[0.78, 0.92]
Race/Ethnicity (vs White British)						
Asian British				0.68		[0.36, 1.28]
Black British				0.79		[0.43, 1.47]
Other British				0.65		[0.32, 1.31]
Age				0.92		[0.75, 1.13]
Male				1.95	***	[1.60, 2.39]

*p < 0.05; **p < 0.01; ***p < 0.001

Table 22 displays the results of logistic regressions of clinical levels of externalizing behavior at age 14 for both males and females. Although the estimates of TBI tend toward increases in the likelihood of clinical levels of externalizing behavior, neither estimate is statistically significant. However, other early-life factors do significantly increase the odds of externalizing behavior, such as maternal smoking during pregnancy and early-life behavior problems.

Table 22. Logistic Regressions of Injury Status Category Predicting Clinical Levels of Externalizing Behavior at Age 14 by Sex (N=11,714)

	Males (N=5,877)			Females (N=5,3,77)		
	OR		95% CI	OR		95% CI
Injury Status						
No Injury	0.90		[0.67, 1.21]	1.22		[0.80, 1.25]
Orthopedic Injury	REF			REF		
Traumatic Brain Injury	1.21		[0.90, 1.62]	1.10		[0.93, 1.48]
Early-Life Risk Factors (age 9 months)						
Low Birthweight (<2.5kg)	1.22		[0.69, 2.17]	0.67		[0.60, 1.62]
Birth Complications	0.90		[0.68, 1.18]	0.82		[0.69, 1.10]
Neurological Deficits	1.28		[0.70, 2.32]	1.44		[0.82, 2.15]
Maternal Smoking Behaviors						
Never Smoked During Pregnancy	REF			REF		
Stopped Smoking During Pregnancy	1.23		[0.82, 1.85]	1.15		[0.87, 1.67]
Smoked Throughout Pregnancy	2.22	***	[1.69, 2.91]	2.31	***	[1.79, 2.78]
Maternal Alcohol Use During Pregnancy	1.23		[0.94, 1.61]	0.74		[0.85, 1.33]
Clinical Hyperactivity (age 3)	2.30	***	[1.64, 3.24]	2.35	***	[1.73, 3.03]
Clinical Conduct Problems (age 3)	1.74	***	[1.33, 2.29]	2.05	***	[1.45, 2.29]
Cognitive Abilities (age 3)	1.00		[0.99, 1.00]	0.99	***	[0.99, 1.00]
Highest Parental Education	0.85	**	[0.77, 0.94]	0.84	*	[0.78, 0.92]
Race/Ethnicity (vs White British)						
Asian British	0.76		[0.31, 1.84]	0.53		[0.36, 1.28]
Black British	0.94		[0.47, 1.88]	0.51		[0.43, 1.47]
Other British	0.46		[0.20, 1.05]	1.04		[0.32, 1.31]
Age	0.86		[0.66, 1.11]	1.11		[0.75, 1.13]
Male						

$*p < 0.05$; $**p < 0.01$; $***p < 0.001$

Alternative Coding of TBI

Table 23 presents the results of logistic regressions predicting a binary measure of delinquent behavior at age 14, using an alternative coding scheme for TBI. This coding scheme more closely mirrors others used in criminological research and combines the OI and NI categories. Model 1 displays the bivariate estimates, while Model 2 displays the multivariate estimates. In Model 2, TBI is significant associated with a 16% increase in the odds of being delinquent at age 14, compared to those who do not have head injuries (OR = 1.16, 95% CI [1.01, 1.34]). Model 3 includes delinquent behavior at age 11 as a control. When this variable is accounted for, the effect of TBI is attenuated and no longer significant. Instead, prior delinquent behavior is associated with a 155% increase in the odds of being delinquent at age 14 (OR = 2.55, 95% CI [2.25, 2.88]).

Table 23. Logistic Regression using Alternative Coding of Traumatic Brain Injury Predicting Delinquency at Age 14

	Model 1 N=8,385			Model 2 N=8,385			Model 3 N=11,714		
	OR		95% CI	OR		95% CI	OR		95% CI
TBI (vs nTBI)	1.25	**	[1.09, 1.43]	1.16	*	[1.01, 1.34]	1.09		[0.97, 1.23]
Delinquency (age 11)							2.55	***	[2.25, 2.88]
Early-Life Risk Factors (age 9 months)									
Low Birthweight (<2.5kg)				0.76		[0.53, 1.09]	0.71	*	[0.53, 0.95]
Birth Complications				1.00		[0.88, 1.14]	0.98		[0.87, 1.09]
Neurological Deficits				0.78		[0.54, 1.12]	0.76	*	[0.58, 1.00]
Maternal Smoking Behaviors									
Never Smoked During Pregnancy				REF			REF		
Stopped Smoking During Pregnancy				1.74	***	[1.43, 2.11]	1.64	***	[1.38, 1.95]
Smoked Throughout Pregnancy				1.70	***	[1.42, 2.03]	1.78	***	[1.54, 2.06]
Maternal Alcohol Use During Pregnancy				1.18	*	[1.04, 1.35]	1.14	*	[1.01, 1.28]
Clinical Hyperactivity (age 3)				1.09		[0.86, 1.38]	1.06		[0.88, 1.27]
Clinical Conduct Problems (age 3)				1.16	*	[1.01, 1.34]	1.13	*	[1.00, 1.28]
Cognitive Abilities (age 3)				1.00		[1.00, 1.00]	1.00	**	[1.00, 1.00]
Highest Parental Education				1.01		[0.96, 1.07]	1.01		[0.96, 1.05]
Race/Ethnicity (vs White British)									
Asian British				0.34	***	[0.26, 0.45]	0.35	***	[0.28, 0.44]
Black British				0.53	**	[0.33, 0.83]	0.55	***	[0.39, 0.78]
Other British				0.60	*	[0.41, 0.89]	0.53	***	[0.38, 0.73]
Age				1.42	***	[1.24, 1.63]	1.34	***	[1.20, 1.49]
Male				1.13		[1.00, 1.27]	1.11		[0.99, 1.24]

*$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

DISCUSSION AND CONCLUSION

DLC theories of criminal behavior place importance on early-life traumas as risk factors for later criminal behavior. While increasing attention has been given to the relationship between TBI and criminal behavior, few studies have examined its influence as an early-life risk factor for delinquency. Childhood TBI presents a unique and potentially severe detriment to neuropsychological development, which may underscore its influence on later criminal behavior. Moffitt's dual taxonomy theory posits that trauma, such as TBI, would lead to earlier onset of delinquent behavior and more serious delinquency in adolescence (Moffitt 1993; Moffitt and Caspi 2001). Prior studies have explored the correlates and prevalence of TBI in offender and adult populations, but much is still unknown about the influence of childhood TBI on later criminal behavior.

The present thesis explores the relationship between childhood TBI and adolescent delinquency, while accounting for other early-life risk factors and methodological recommendations from clinical studies. Data from the MCS are used to obtain prospective reports of TBI throughout childhood and self-reports of delinquent behavior in adolescence. DLC theories of crime provide reason to expect that childhood TBI would be influential only for more serious delinquent behavior, such as earlier onset of or greater variety in delinquent behaviors. Consistent with these expectations, I find that childhood TBI increases the likelihood of initiating delinquent behavior by age 11 but is not predictive of delinquency onset by age 14. Additionally, childhood TBI is predictive both of participation in a greater variety of delinquent behaviors at age 14 and of maintaining delinquent behavior from ages 11 to 14. Findings from the current study also offer a basis for further exploration of developmental period effects and sex differences in the effects of TBI. Overall, these findings support the consideration of TBI as an early-life risk factor for later, serious criminal behavior and support the continued exploration of nuance in the relationship between TBI and crime.

As studies on the effects of TBI become more commonplace in criminology, it is important to incorporate methodological considerations from clinical studies. The use of the OI group as a negative control represents one such methodological consideration. In many prior studies, it is assumed that the only distinguishing factor between those with head injuries and those in the control group is the presence of a head injury (Fazel et al. 2011; Timonen et al. 2002; Yeates and Taylor 2005). However, it is likely that there are other early-life factors that would influence the occurrence of any injury, whether to the body or to the head, such as self-control (Gottfredson and Hirschi 1990). Findings from this study support the need for distinction between NI, OI, and TBI groups. For instance, conduct problems at age 3 increase the odds of getting an OI or a TBI, compared to reporting NI. Additionally, maternal substance use during pregnancy increases the likelihood of reporting a TBI, compared to reporting NI; however, maternal substance use during pregnancy is not significantly associated with increased likelihood of TBI, compared to OI. By using OI as a comparison group, possible bias and confounders in the relationship between TBI and criminal behavior are implicitly controlled.

Although some studies find significant associations between TBI and crime (Fazel et al. 2011; Fishbein et al. 2016; Timonen et al. 2002), others find that these associations become non-significant at conventional levels when using an OI comparison group (Bonow et al. 2019; Kennedy et al. 2017). The findings from this thesis confirm the need to be aware of how the reference group can affect estimates of TBI effects. Using OI as a negative control group produces more conservative estimates (Yeates and Taylor 2005). When comparing to the OI group, TBI is not a statistically significant predictor of age 14 delinquency but is still a significant predictor of delinquency at age 11 and more serious delinquent behavior at age 14. When comparing to the NI group, TBI appears to be a significant predictor of all those behaviors but could represent an over-estimation of the effects of TBI on delinquent behaviors. This finding is further supported by the results of the supplementary model that uses an alternative coding scheme for head injury to predict delinquency at age 14 (Table 23). In this model, the effect of TBI is larger than the primary models indicate and reaches the level of statistical significance.

The findings from this thesis largely support prior evidence of a relationship between TBI and later criminal behavior (Bonow et al. 2019; Fazel et al. 2011; Fishbein et al. 2016; Kennedy et al. 2017; Schwartz et al. 2017; Timonen et al. 2002). The present study adds to the body of knowledge in this area by expanding on a great deal of nuance present in this relationship. The primary analyses examine how childhood TBI influences delinquency onset and severity, and additional analyses explore sex differences and how timing of injury influences later delinquent behavior.

In general, support is found for Hypotheses 2 and 3. Childhood TBI significantly increases the likelihood of early-onset delinquency, but it is not significantly associated with adolescent-onset delinquency at age 14. Given that any delinquency at age 14 might be more normative (Moffitt 1993), it is important to determine how childhood TBI might influence more serious delinquent behavior at age 14. In fact, childhood TBI is significantly associated with increased odds of persisting in delinquent behavior from age 11 to 14 and participating in a greater variety of delinquent behaviors at age 14. These findings largely conform to expectations based on Moffitt’s dual taxonomy theory (Bushway 2012; Moffitt 1993; Moffitt and Caspi 2001). The findings indicate that childhood TBI might push individuals toward life-course persistent offending behavior, which is marked by earlier onset and greater severity, even in adolescence (Bushway 2012; Moffitt 1993).

On the other hand, childhood TBI might not be predictive of adolescent delinquent behavior if it is more normative or socially influenced, such as trying alcohol with friends. Although it is merely speculation, I believe that the non-significance of childhood TBI in predicting the binary measure of delinquent behavior at age 14 supports the idea that minor delinquent behavior in middle adolescence is largely influenced by social factors, rather than early-life risk factors, such as TBI. The prevalence of delinquent behaviors increases from about 30% at age 11 to over 50% at age 14. It is also possible that any effect of TBI on delinquent behavior at age 14 is diluted by the sheer number of cohort members who engage in some form of delinquency. The attrition analysis (Table A1) indicates that the non-significance of TBI effects on age 14 delinquency cannot be attributed to individuals with TBI dropping out of the sample.

The breadth of the data available in the MCS allow for additional explorations of the relationship between TBI and criminal behavior. While several scholars have pointed out the need for investigation of sex differences in the effects of TBI (Farace and Alves 2000; Munivenkatappa et al. 2016; Williams et al. 2018), relatively few datasets allow for sufficient samples of females and males with histories of both TBI and delinquent behavior. Current methodological discussions within criminology limit the utility of determining statistical differences in estimates for males and females, but general trends can be discussed and can motivate future research. Although estimates for TBI trend toward increasing the likelihood of delinquent behavior, most of the estimates do not reach the level of statistical significance. The only exception occurs when examining how TBI is associated with variety of delinquent behaviors at age 14. For males, childhood TBI is significantly associated with a 15% increase in the odds of participating in an additional delinquent behavior. For females, reporting NI is significantly associated with a 12% decrease in those odds, which may suggest that having any sort of injury is a risk factor for female delinquency. The effects for TBI all trend in the same directions between males and females, so TBI may have similar effects between males and females.

Few studies have examined how timing of injury matters for later behavior (Kennedy et al. 2017), but there is reason to believe that head injuries that happen earlier in life will have more detrimental effects on behavior than those that occur later in life (Guilhaume-Correa et al. 2020; Zhao et al. 2018). The analyses of developmental period effects seem to support other findings that earlier trauma will be more influential on future behavior (Barker et al. 2010; Eslinger et al. 2004). In bivariate analyses, TBI, compared to OI, is significantly associated with delinquent behavior at age 11 for each of the developmental periods of interest. Once the other early-life risk factors are included in the models, only TBI from ages 3-5 is predictive of early-onset delinquency, suggesting that early injury may be more influential than later injury. None of the models indicate that TBI at a certain period is predictive of delinquent behavior at age 14. That finding is not surprising given that TBI over the entire range of 3-11 was not significantly predictive of delinquency at age 14. TBI from ages 11 to 14 trended toward increasing the likelihood of delinquency at age 14, but the estimates never reach conventional levels of statistical significance.

However, those with NI, compared with OI, were significantly less likely to be engaged in delinquent behavior across many of the models. This finding may suggest that those with any type of injury are riskier and more prone to delinquency than those with no injury, possibly due to other underlying risk factors, such as low self-control (Beaver et al. 2007; Gottfredson and Hirschi 1990; Schwartz et al. 2017). In this case, injury would not necessarily be leading to criminal behavior, but they may share similar risk factors. When considering adolescent-onset delinquency, social factors, such as having delinquent friends, are potentially more influential than early-life risk factors in determining participation in low-level delinquency. Alternatively, it is possible that injury, especially injuries during the age 11 to 14 timeframe, could arise as a direct consequence of participation in delinquent behavior.

The analyses of TBI predicting externalizing behavior offer a slightly different conceptualization of problematic behaviors in early and middle adolescence. Cohort members may act out in ways that are not necessarily delinquent, which would be missed in the primary analyses. TBI is a significant predictor of increases in the odds of having high levels of externalizing behavior at age 11, for both the whole samples and males, specifically. The non-significance of the estimate for the female subsample might point to differences in expression of problematic behaviors after injury. Males are more likely to exhibit externalizing behavior, while females may be more likely to exhibit internalizing behavior (Scott et al. 2015). Similar to the findings from models of delinquency, TBI is not a significant predictor of high levels of externalizing behavior at age 14, net of controls. The measure of externalizing behavior is a binary measure for whether or not individuals met a threshold for clinical levels of behavior. It is possible that a count or continuous measure of externalizing behavior would show significant associations with TBI, much like the variety score of delinquent behaviors does.

Overall, the present thesis implicates TBI as an important early-life risk factor for delinquent behavior, especially delinquent behavior that is consistent with life-course persistent offending. Most criminological studies of TBI focus on prevalence rates and correlates of injuries within offender samples (Perron and Howard 2008; Schwartz et al. 2017; Vaughn et al. 2014). While much of this literature points to TBI as influential in the initiation of criminal behavior, very few studies have been able to assess this relationship longitudinally and in a sample of non-incarcerated individuals (Bonow et al. 2019; Kennedy et al. 2017). The findings from this study add to that body of knowledge and provide additional support for TBI as a potential cause of criminal behavior.

Ethical Considerations and Implications

Since research on TBI is relatively new, it does pose some interesting avenues for exploration within criminology and criminal justice. However, there are a few minor ethical issues that may arise when researching TBI. In recent years, public interest in TBI has rapidly grown, largely due to increased attention to head injuries in football players and chronic traumatic encephalopathy (CTE). As such, I feel it is important to be aware of the possible audiences for any research regarding TBI and its associated behavioral outcomes. Findings in both criminological and clinical literatures have a tendency to inform policy and treatment decisions, which are necessarily delicate subjects. Treatment and prevention of TBI and related neuropsychological trauma may soon fall under the focus of the criminal justice system as connections with crime continue to arise (Focquaert 2019; Vaske 2017). While it is not controversial to say that TBI should be avoided and prevented when possible, it is important remain aware of the potential negative aspects of focusing on biological explanations of criminal behavior. For that reason, findings from this work should be evaluated along with the broader scientific consensus, in order to avoid any rash decisions or proclamations about the possible effects of a childhood TBI, regardless of the direction of the findings.

Strengths and Limitations

The present thesis has several limitations, many of which are common in the study of TBI and many of which also can be seen strengths. First, the sample used is not a clinically defined sample. That is, those who report TBI or OI have not been diagnosed by a physician or assessed according to a standardized scale. Instead, the sample is based on parent-reports of their children's injuries. Unlike clinical samples, severity cannot be assessed with the current data. Therefore, all TBIs are treated as equifinal, as opposed to variable depending on injury severity. However, as mentioned previously, the use of a non-clinical sample also offers benefits in terms of generalizability, especially since many people with mild TBIs do not seek medical attention (Demakis and Rimland 2010). However, within this sample, over 90% of the cohort members received medical attention for their head injuries. This stark difference between estimates of medical treatment may be due to healthcare differences between the United States and the UK. Because the overwhelming majority of individuals received some form of medical attention for their injuries, the estimates presented in this thesis are likely to be conservative, as proper treatment may mitigate negative consequences of TBI.

Furthermore, this sample differs from many others in that injuries are reported by the parents. Parent-reports of injuries may suffer from social desirability bias. Parents could refrain from reporting injuries their child experienced in order to seem like more competent parents. Additionally, injuries might not be reported by parents if the parents themselves were the cause of the injury, as is the case in child abuse. On the other hand, parent-reports of early childhood injuries may be more accurate than retrospective self-reports. Forward telescoping and forgetfulness may plague self-reports of injury that occurred during childhood. Prospective parent-reports of injury can capture occurrences of injury that the children themselves may not remember happening.

Although developmental period effects are explored in this study, further work is needed to offer more concrete conclusions. The developmental periods utilized in the present study are not necessarily based on key developmental milestones; instead, they are based on the waves of data available. More specific data on developmental timing and achievement of psychological, pubertal, and social milestones would be needed to flesh out the variation in TBI effects throughout the lifespan. This data should also capture a wider age range, since neither development nor delinquency stops at age 14. Data from the next wave of the MCS may be useful in this endeavor.

Similarly, future studies should aim to examine sex differences in the relationship between TBI and crime more fully. The present study is one of the first to examine sex differences, but conclusions from the analyses are limited. Future analyses of sex differences in the behavioral effects of TBI should also take into account social factors that would influence either the incidence of TBI or behavioral change after TBI. Those social factors, such as opportunity, deviant peers, and parental supervision may differ more drastically between males and females than the actual head injury does.

Lastly, this study is currently limited in its ability to assess mechanisms underlying possible behavioral changes after TBI. The neurological damage and subsequent changes in function that can arise after TBI are not explicitly included in the present analyses. However, there is reason to believe that changes in self-control and emotional regulation post-injury are more proximate causes of criminal behavior than the injury itself (Milders et al. 2008; Schwartz et al. 2017). Additionally, identification of specific mechanisms might reveal stronger connections with certain types of criminal behavior. Some studies have attempted to assess changes in self-control after head injury, but more research is needed (Schwartz et al. 2017). Furthermore, external factors may change after injury. For instance, parental supervision might increase, following an injury, which could lead to decreases in criminal behavior. Future studies should aim to account for the breadth of changes that occur post-injury, both internally and externally.

Conclusion

In sum, the present study contributes to biosocial and DLC criminology in finding that TBI can and should be considered an early-life risk factor for early and serious delinquent behavior in adolescence. Even when other relevant early-life risk factors are accounted for and conservative tests from clinical literature are utilized, childhood TBI presents a significant risk for early-onset delinquent behavior and more serious delinquent behavior in adolescence. The findings only scratch the surface in uncovering nuance within the relationship between TBI and criminal behavior. Future work should continue to explore this relationship in both general and offender populations, to capture the vast variation in the behavioral effects of TBI.

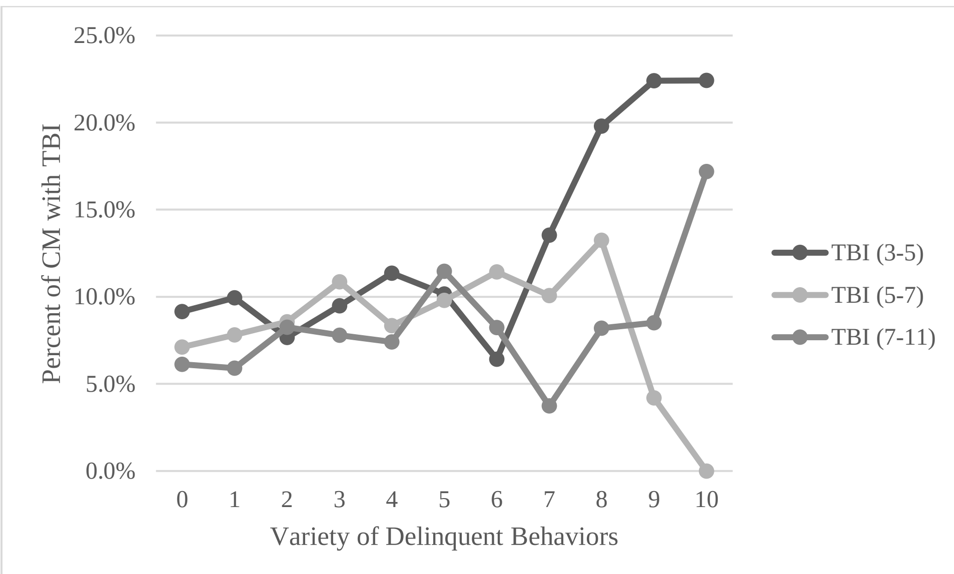
APPENDIX

Table A1. Bivariate Logistic Regression of Traumatic Brain Injury Predicting Attrition (N=13, 260)

	OR	95% CI
Injury Status		
No Injury	1.06	[0.93, 1.22]
Orthopedic Injury	REF	
Traumatic Brain Injury	1.04	[0.90, 1.21]

*p < 0.05; **p < 0.01; ***p < 0.001

Figure A1. TBI at Developmental Periods by Variety of Delinquent Behaviors



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