Convergence
A Journal for Young Researchers

ORIGINAL REVIEW

Received: 2-25-26; Accepted: 6-3-26;
Managing Editor(s): Jonas Katona;
Action Editor(s): Amy Nguyen

Variations in Neuroplasticity Following Traumatic Brain Injury: A Comparison Across the Life Span

Jagriti Khare

Dover Court International School, Singapore

Abstract

Traumatic brain injury (TBI) represents a significant worldwide health concern, resulting in long-term disability and/or mortality. Annually, it is estimated that approximately 64-74 million individuals experience a TBI, impacting cognition, emotions, and motor abilities throughout all life stages. Recovery depends largely on neuroplasticity, which enables the brain to reorganise itself through the formation of new neural connections, although the effectiveness of this process differs with age. The effect of TBI on plasticity is not properly understood across different age groups. This literature review examines the variations in brain plasticity throughout an individual's life (specifically children, adolescents, adults, and the elderly) following a TBI. Evidence indicates that, although children and adolescents exhibit increased neural adaptability and higher plasticity, it does not consistently lead to the most effective functional recovery. Conversely, adults and seniors typically exhibit more limited yet stable plasticity and reorganization. This is based on the analysis of current academic research, including neuroimaging studies, clinical trials, and long-term examinations of TBI and neuroplasticity among various age groups. In general, it is crucial to understand age-related variations in neuroplasticity following a TBI. This is essential for developing recovery strategies and enhancing future clinical and research techniques related to TBI.

Keywords: traumatic brain injury (TBI), neuroplasticity, lifespan, pediatric traumatic brain injury, adolescent brain development, adult neurorehabilitation, geriatric traumatic brain injury, functional recovery outcomes, synaptic plasticity

1. Methodology

A narrative literature review approach was used here to investigate age-related variations in neuroplasticity following TBI. Some of the databases used for the literature searches were Google Scholar, PubMed, ScienceDirect, and APA PsycNet. Key terms included traumatic brain injury (TBI), neuroplasticity, ageing, children, adolescents, adults, elderly, recovery, long-term depression, long-term potentiation, brain-derived neurotrophic factor (BDNF), diffuse brain injury, synaptogenesis, etc. Studies that were analysed include peer-reviewed articles, longitudinal studies, clinical studies, neuroimaging studies, and experimental studies published primarily in English. Articles that specifically examined neuroplastic mechanisms and recovery outcomes following TBI across different age groups were prioritized.

2. Introduction

Traumatic brain injury (TBI) is a major global health problem, and it is one of the leading causes of mortality (Maas et al., 2017) across all age groups. It refers to alterations in brain function or other signs of brain disease caused by an external force, which can occur on the road, at home, at work, during war, or even while playing sports (Manley & Maas, 2013). This can lead to physical, social, cognitive, and emotional impairments of different severities. Following a brain injury, the brain undergoes a process called neuroplasticity, resulting in adaptive functional and structural modifications. It is described as the nervous system's capacity to reorganize its structure, functions, or connections in response to internal or external stimuli following injuries like TBI or stroke (Puderbaugh & Emmady, 2025). This process is supported by molecular and cellular mechanisms such as synaptic plasticity (e.g., long-term potentiation and depression), neurotrophic factors such as brain-derived neurotrophic factor (BDNF), and structural changes including synaptogenesis, all of which may vary across the lifespan (Bear & Malenka, 1994; Gustafsson et al., 2021; Su et al., 2016).

According to Zamani et al. (2020), the effects of TBI vary across developmental stages. While children's brains generally show higher flexibility, some of the cognitive and behavioral abnormalities only emerge during adolescence or early adulthood.

In this review, children are defined as individuals aged 0-12, adolescents as 13-18 years, adults as 19-64 years, and the elderly as 65 years and above.

In children, early TBI can disrupt normal brain function and hinder the development of neural networks crucial for social behavior. However, the effectiveness of neuroplasticity in helping recovery depends on various factors such as pre-existing conditions, individual characteristics, the circumstances surrounding and following the injury, age, and the nature of the injury itself (Zamani et al., 2020)

In adolescents, TBI can lead to consistent executive functioning deficits in everyday life (Catharine et al., 2019). Linking to plasticity, it may not always be defined as beneficial for adolescents, as it consists of multiple processes needed to be regulated (Giza & Prins, 2006).

In adults, TBI increases the risk of neural degradation, which could include Alzheimer's. Consequently, this could negatively affect the recovery of adults in the cognitive and neurological aspects (Rajan, 2025). However, full recovery remains possible, depending on the severity of the injury and other personal factors.

For the elderly, Tan et al. (2025) found that across 18 of their studies, fewer than half regained full functional independence, which shows that older adults have the greatest difficulty recovering completely compared to other age groups.

Understanding how neuroplasticity functions across developmental stages is crucial for evaluating recovery results following TBI in light of these age-related differences. This literature review will contrast a variety of academic studies examining children, adolescents, adults, and the elderly. It focuses on how brain plasticity is affected following TBI. The paper will first look at neuroplastic responses in children and adolescents and then analyse recovery patterns in adults and the elderly. Each component will assess how the developmental stage affects recovery outcomes by interacting with variables such as injury severity and timing of injury. Furthermore, in order to find broad trends in neuroplasticity throughout the lifetime, the review will synthesize the similarities and differences between age groups. Finally, this paper will analyse how this information can help to provide more insight into future endeavors in this specific field of neuroscience.

3. Traumatic brain injury and neuroplasticity

Neuroplasticity underlies recovery following TBI, but the extent of these neural changes is influenced by factors such as age, injury severity, and stage of rehabilitation.

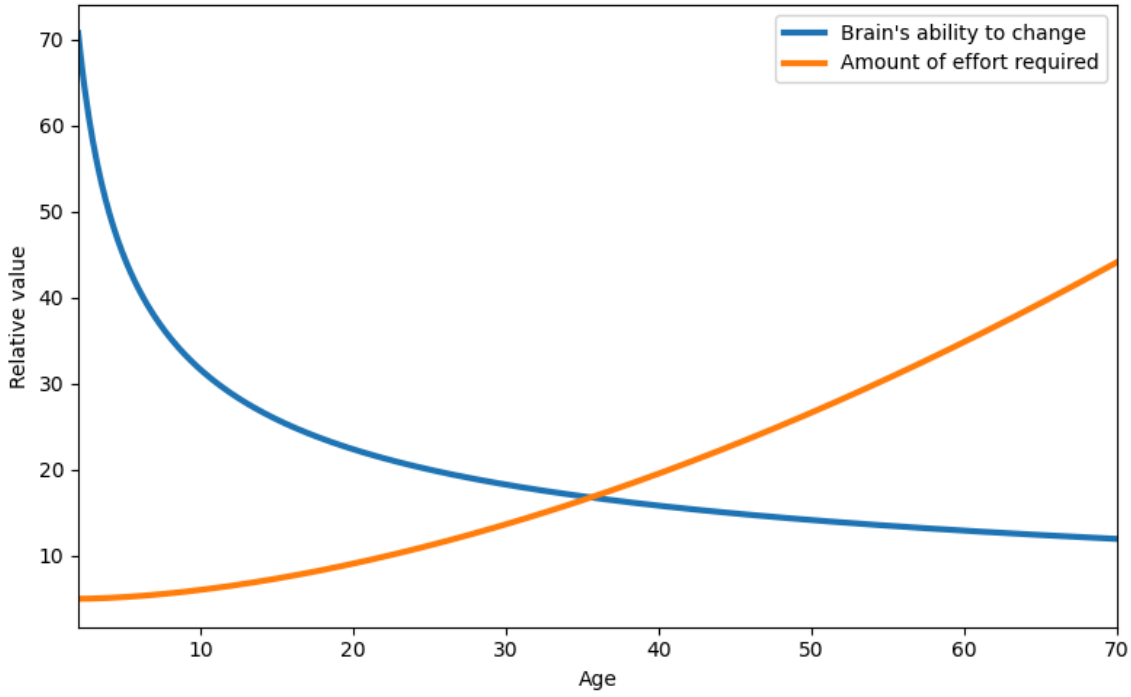

Figure 1: Author-generated illustration showing the inverse relationship between the brain's capacity for change and the effort required for such change across age. The figure is adapted conceptually from Levitt (2019).

Existing literature suggests that the brain's capacity to adapt in response to experiences diminishes with age, while the effort required to achieve functional recovery increases (Figure 1). This indicates that younger individuals may exhibit greater neuroplastic potential following TBI, enabling more efficient neural reorganization, whereas older individuals may require more intensive rehabilitation to achieve comparable recovery outcomes.

In the context of TBI, immediately after injury, there is cell death, along with a reduction in cortical inhibitory pathways for 1 to 2 days, which may facilitate the recruitment of new neural networks and promote early circuit reorganization (Nahmani & Turrigiano, 2014; Su et al., 2016). Cortical circuits gradually shift from inhibitory to excitatory activity; surviving neurons initiate axonal sprouting and synaptogenesis, forming new connections that help repair damaged circuits and restore functional pathways (Su et al., 2016). Neuronal and non-neuronal cells, including endothelial progenitors, glial cells, and inflammatory cells, are recruited to replace weakened cells and support revascularization (Burda & Sofroniew, 2014; Su et al., 2016). Additionally, these cells promote gliotic scar formation—a process where dense glial tissue isolates the injury but also inhibits the regrowth of neurons (Wang et al., 2018). At the cellular level, microglia and astrocytes initiate an inflammatory response after injury. These cells will then secrete a variety of cytokines, chemokines, and growth factors, which determine the extent of the damage and the following repair (Karve et al., 2016). Circulating endothelial progenitor cells (EPCs) may be crucial for both healthy and pathological angiogenesis in adults (Wei et al., 2010). Angiogenesis is a complex process of forming new blood vessels and is essential for growth and balance (Swerlick, 1995). It is regulated by molecular signals such as vascular endothelial growth factor, which help in endothelial cell proliferation, promoting angiogenesis (Gong et al., 2011). Additionally, glial cells actively influence neuroplasticity, which enables highly adaptable control over neuronal excitability, synaptic transmission, and network synchronization (Dzyubenko and Hermann, 2023). At the circuit level, these processes lead to large-scale cortical reorganization, including the recruitment and remodeling of cortical motor representations that support functional recovery following TBI (Pruitt et al., 2017).

Therefore, these processes, including angiogenesis supported by EPCs and the neuroplasticity influenced by glial cells, together play a crucial role in recovery after TBI. Several weeks after the injury, increased expression of synaptic markers and enhanced axonal sprouting are observed. This enables neural remodeling and cortical reorganization that contribute to functional recovery (Su et al., 2016).

In individuals with brain injuries, adaptive neuroplasticity can be modulated by rehabilitation procedures, increasing everyday life activities and lowering motor impairment (Johnson & Cohen, 2022). Therefore, after TBI, rehabilitation can be done, which is dependent on the recovery stage of the patient, such as immediately after the injury (acute stage), the main goal of the treatment would be to prevent injury and calm the patient down. After this stage (the chronic stages of recovery), many rehabilitation strategies can be implemented. However, recovery is complicated by age-related variations in plasticity, with younger people showing more plasticity and older adults showing less plasticity and a higher risk of maladaptive alterations (Rajan, 2025).

In general, neuroplastic mechanisms promote recovery after traumatic brain damage because they allow for the gradual structural and functional reorganization of neuronal networks. To enhance adaptive neural pathways and improve function, biological processes such as synaptogenesis, angiogenesis, and glial cell regulation work together with rehabilitation interventions. The efficacy of these neuroplastic mechanisms varies because age, the severity of the injury, and the stage of recovery all affect how well rehabilitation can support long-term recovery results.

4. Neuroplasticity in Children and Adolescents after TBI

In children and adolescents, the degree and effectiveness of neuroplasticity after TBI are strongly dependent on developmental stage and injury severity. Neuroplasticity after TBI differs significantly between children and adolescents, demonstrating that the degree and efficacy of plasticity vary across the lifetime. Various processes play a role in this mechanism of neuroplasticity of younger individuals, such as the excessive production and removal of neurons and synapses, along with the stabilization of synapses depending on the activity (Johnston et al., 2009). The activity-dependent stabilization is the strengthening of circuits that are repeatedly activated, shaping long-term connectivity (Chaudhury et al., 2016). The pediatric brain exhibits greater neuroplasticity compared to the adult brain, facilitating the rapid acquisition of new skills and the recovery from cerebral injuries (Johnston et al., 2009). Mechanistically, this heightened plasticity is supported by LTP (Long-term potentiation) and LTD (Long-term depression). LTP is a process that helps in synaptic enhancement and increases synaptic strength (Bear & Malenka, 1994; Johnston et al., 2009), whereas LTD is the process of the reduction of synaptic efficacy (Bliss & Cooke, 2011). Interruption of these processes by TBI in children can disrupt normal circuit maturation, leading to prolonged cognitive and adaptive impairments. Additionally, experimental animal models of TBI using juvenile rats show that injury alters brain-derived neurotrophic factor (BDNF), a crucial factor for activity-dependent synaptic plasticity. These changes are observed in both mRNA and protein levels in the hippocampal and cortical areas following the injury (Gustafsson et al., 2021). This suggests that the developing brain may sometimes recover slowly or incompletely, possibly indicating age-related disruptions in synaptic plasticity mechanisms, rather than solely reflecting observed cognitive deficits.

However, the molecular mechanisms for synapses depending on activity have yet to be elucidated (Johnston et al., 2009). Age of injury is a very important factor because younger children have a higher risk of diffuse brain injury, the process of widespread axonal damage in the aftermath of TBI (Su et al., 2016), and this can have dangerous effects on their growth and development (Treble-Barna et al., 2017). The severity of TBI is also a crucial factor, as significant severity is associated with long-term damage (Treble-Barna et al., 2017). A study showed that children who had a severe TBI when they were young showed impairments in adaptive functioning as a result of neuropsychological tests and interviews after 6.9 years of injury (Treble-Barna et al., 2017). Observing the results, the children in this study showed deficiencies in processing speed and fluid reasoning. Slowing down processing speeds can make it difficult to do everyday tasks such as understanding verbal remarks or dealing with a fast work environment (Treble-Barna et al., 2017). Integrating both age and severity, younger age at injury was linked to little to no recovery for children who have severe TBI, but older children showed better results. Although newborns (ages 0-2.11 years) with moderate TBI had a worse outcome than older children with injuries of similar severity (Anderson et al., 2005).

During adolescence, ongoing synaptic pruning (the targeted elimination of functional synapses; Sakai, 2020) and cortical maturation (enabling cognitive and behavioral functioning, measured by thickness and curvature; Deoni et al., 2015) make the brain more sensitive to TBI, resulting in more consistent deficits compared with injuries sustained earlier in childhood. Due to continuous neuronal growth during this delicate developmental stage, reviews by Mulligan et al. (2022) and Chan et al. (2024) show that traumatic brain damage received throughout adolescence is associated with worse recovery results than injuries sustained earlier in childhood. Through the process of synaptic pruning, cortical structures undergo significant remodeling. This process results in a decrease in cortical gray matter alongside an acceleration of axon density and myelination - the formation of a specialized myelin membrane around axons – leading to an increase in

white matter volume. These processes can lead to better cognitive abilities and social cognition (Mulligan et al., 2022). Therefore, any interruptions to these processes can lead to harmful consequences (Chan et al., 2024). These developmental processes are closely connected to underlying synaptic plasticity mechanisms, and disruptions in pruning and myelination may impair activity-dependent plasticity. Thus, this contributes to poorer recovery outcomes following TBI during adolescence (Sakai, 2020; Mulligan et al., 2022).

Comparing the severity of TBI, a study conducted by Kolstø et al. (2025) showed that a mild TBI in adolescence can be associated with mainly improved functional outcomes; however, patients (from age 0 to 17) showed more neurological damage and a more severe clinical condition. Also, a population-based outcome study conducted in Norway presented that 87% of all the children/adolescents included in the study with a mild TBI showed improved recovery compared to the 59% of adolescents with severe TBI (Olsen et al., 2022).

Overall, the relationship between developmental stage and injury severity shapes neuroplasticity in children and adolescents after TBI. Disturbances during crucial stages like adolescence can result in long-lasting neurological and cognitive impairments, even if ongoing neuronal reorganization in the growing brain might aid in healing. As a result, recovery results depend not only on neuroplastic potential but also on the timing and severity of the damage.

5. Neuroplasticity in Adults after TBI

In adults, neuroplasticity following TBI is present but happens more slowly and with greater limitations compared to earlier stages of development. In order to preserve cognitive function, adults rely on compensatory processes (Rajan, 2025), which occur when the body tries to readjust and compensate for the stresses it is under (Kauffman, 2015). Even though plasticity decreases with age, new neurons can still be created throughout life; therefore, it does not completely stop generating (Rajan, 2025). Mechanistically, adult neuroplasticity involves activity-dependent processes such as LTP. A study conducted by Weston et al. (2021) investigated adult male rats that received a moderate TBI. Measurements of LTP showed prolonged impairment, which worsened between 30 and 60 days (Weston et al., 2021). In addition, adult TBI causes a neurological deficit through complex mechanisms including glutamate excitotoxicity, inflammation, demyelination, programmed cell death, and the development of edema. This is caused by glial cells, and they play a crucial role in the CNS response, damage control, and regeneration. In response to tissue damage, these cells activate, undergo hypertrophy, and proliferate, eventually forming a glial scar. This scar acts as a barrier within the damaged tissue, protecting the CNS during the acute phase following the injury (Amlerova et al., 2024). These molecular and cellular mechanisms provide a biological basis for the partial functional recovery seen in adults.

The brain's tendency toward neuroplasticity enables it to partially compensate for these disruptions caused by TBI by creating new connections and rerouting neural pathways. Neuroplasticity plays a role in both compensatory behavior and potential functional maladaptation in the process of recovering from brain damage in adults. Compensating is when the brain shifts activities to unaffected areas to retain or restore function after brain damage. This adaptive reaction often results in enhanced performance in previously degraded tasks. On the other hand, maladaptation refers to the traits or characteristics that reduce fitness or performance in a population (Brady et al., 2019) and can occur when compensatory processes inadvertently prevent optimal healing (Zotey et al., 2023). There is also a significant difference related to recovery and severity of TBI in adults. A study conducted by Othman et al. (2022) showed that out of all the adults with mild TBI, 19.2% showed cognitive damage 3 months after the injury and 19.2% showed neuropsychiatric manifestations.

After 6 months of injury, most of the patients exhibited recovery, while some continued to experience cognitive damage (Othman et al., 2022). However, in the same study by Othman et al. (2022), out of all adults with moderate TBI, 39.3% exhibited cognitive impairment, whereas 25% showed neuropsychiatric manifestations (such as agitation, depression, anxiety, apathy, hallucinations, impulsivity, and aggression; Maristany et al., 2024) after 3 months of having the injury. In the case of 6 months post-injury, none of the patients showed continued cognitive damage or neuropsychiatric manifestations (Othman et al., 2022). According to a review by Wilkins et al. (2019), long-term results after severe traumatic brain damage might be better than previously proposed recovery models. In the study conducted by Wilkins et al. (2019), it is seen that the mortality rate of severe TBI patients was high 3 months after injury; however, for long-term TBI patients, there was significant improvement in functional results 3-24 months after injury, which shows that the long-term prognosis in adults with severe TBI was higher than expected.

After TBI, adults' neuroplasticity is generally slower and less extensive than that of younger individuals; however, compensatory neuronal reorganization still allows a partial functional recovery. The degree of an injury has a significant impact on recovery results: minor injuries typically improve more quickly, whereas severe injuries show gradual, long-term improvements. Adults still have some capacity for brain adaptation, although the degree and quality of recovery are influenced by both maladaptive and compensatory processes.

6. Neuroplasticity in the Elderly after TBI

Older adults exhibit the slowest and least effective neuroplastic responses after a TBI, leading to poorer functional outcomes, higher mortality rates, and higher vulnerabilities to even mild injuries. Chan et al. (2024) reported that TBI recovery declines with age, with older patients showing poorer functional outcomes and higher mortality rates. Atrophy is a condition where the loss of brain cells and neural connections causes brain tissues to decrease (Joseph et al., 2023), and this occurs in the brain as people age. It causes the distance between the brain and skull to expand. This increases the risk of shearing damage to the dural vessels. Also, due to their diminished cerebral reserve, elderly individuals are more susceptible to mild injuries, and many of them have underlying medical issues that are concealed by TBIs (Prasad et al., 2018; Chan et al., 2024). A study conducted by Race et al. (2024) on rodents came to the conclusion that aged rodents had difficulties related to reduced neuroplasticity, dysregulated inflammation, and age-regulated cellular changes, which can affect their recovery after TBI.

In older patients, this leads to poor functional results and higher mortality rates (Chan et al., 2024). Additionally, numerous studies have demonstrated that aged rodents have slower plasticity rates because LTP is decreased while LTD is enhanced (Burke and Barnes, 2006; Kumar, 2011; Sikora et al., 2021; Ridderinkhof and Krugers, 2022). Impaired glutamatergic transmission (the synaptic signaling between neurons mediated by glutamate; Zhou & Danbolt, 2014), cholinergic hypofunction (the reduction of cholinergic system activity; Schliebs and Arendt, 2010), and significant changes in the dopaminergic system (the neural signalling mediated by dopamine that regulates movement, reward and cognition; Klein et al., 2019) all hinder inter-neuronal interaction and may contribute to learning and memory deficits as well as decreased cognitive flexibility as age increases (Wong et al., 2021; Ridderinkhof and Krugers, 2022). These changes reflect a decline in the efficiency of synaptic plasticity mechanisms, which could limit the brain's ability for flexible reorganization after TBI in older adults. A review by Winter et al. (2022) found consistent evidence, considering the severity of TBI, showing worse results for older patients, even though they have milder TBIs. In a comparison of older and younger adults with mild TBI, Thompson et al. (2020) discovered that older adults consistently exhibited lower overall

physical health-related quality of life than their counterparts from one week to one year after injury (Thompson et al., 2020; Chan et al., 2024). Older patients with severe TBI exhibited unfavorable results and a very high mortality rate of 83.3% (Utomo et al., 2009; Chan et al., 2024). Moreover, the treatment of elderly TBI lacks precise guidelines, and those that do exist are mainly based on research involving younger people (Chan et al., 2024).

In comparison to younger age groups, neuroplasticity is generally significantly diminished in the elderly following TBI, which results in a delayed and less successful recovery. Even in mild TBI patients, age-related brain alterations, reduced cerebral reserve, and altered neurotransmission restrict functional results and increase vulnerability to injury. Because rehabilitation programs are not sufficiently tailored to the cognitive and functional needs of older adults (e.g., slower recovery rates, higher fall risk), older persons experience greater mortality rates, worse recovery, and more difficulties.

7. Discussion

Although each age group demonstrates different neuroplastic responses following TBI, there are several common trends that emerge across the lifespan. The evidence reviewed suggests that recovery does not depend solely on the degree of neuroplasticity but also on factors such as developmental stage, injury severity, and age-related biological mechanisms. To provide a clearer comparison of the findings, Table 1 summarizes the key differences across different stages of life.

A key contribution of this review is the integration of evidence directly addressing its aim: to examine variations in neuroplasticity across the lifespan following TBI. The findings show that while neuroplasticity is a universal biological response to TBI, its nature and functional outcome differ significantly between children, adolescents, adults, and the elderly. Children and adolescents demonstrate heightened synaptic activity, BDNF-mediated plasticity, and synaptogenesis, but early or severe TBI can disrupt healthy brain maturation, leading to deficits (Anderson et al., 2005; Mulligan et al., 2022). In adults, neuroplasticity remains in a more limited and compensatory form where the same mechanisms that support recovery can sometimes cause dysfunctional pathways (Zotey et al., 2023). For the elderly, there is reduced LTP, neurotransmitter decline, and brain atrophy, which produces a poor neuroplastic environment for recovery even after mild TBI (Burke and Barnes, 2006; Chan et al., 2024). Clinical data for this group is largely extrapolated from younger patient data, which shows a large gap in research. Altogether, these findings directly address the aim of this paper.

Although children and adolescents have better neuroplasticity than adults, it does not always mean that they will have better long-term recovery after TBI. During childhood and adolescence, the brain is still developing through processes such as synaptogenesis, synaptic pruning, and myelination. If a TBI happens during this crucial time, it can interrupt these processes. These new connections may not develop in the same way as they would in a healthy brain. As a result, younger brains may recover well at first but could later experience cognitive or behavioral difficulties in adolescence or adulthood.

For rehabilitation strategies, the primary goal of treatment during the acute phase (which occurs in the hours right after an accident) is to stabilize the patient and concentrate on preventing additional harm. The results of a study done by Winter et al. (2022) verify that age moderates the impact of injury severity on functional trajectory. Therefore, an individual's age at the time of injury determines the predictive validity of injury severity for functional trajectories. However, most rehabilitation strategies are based on severity and are dependent on the recovery stage of the patient (Chan et al., 2024). These results point to a discrepancy between current clinical practice and study findings.

Incorporating both age and injury severity into rehabilitation planning allows clinicians to optimize recovery outcomes. By tailoring interventions to a patient's developmental stage and the extent of their injury, functional improvements can be enhanced and long-term deficits reduced.

Table 1: Comparison of neuroplastic mechanisms and recovery characteristics across the lifespan following TBI.

Lifespan stage	Neuroplasticity level	Key mechanisms	Typical TBI response	Main limiting factors
Children and adolescents	High but developmentally sensitive	Synaptogenesis, synaptic pruning, LTP/LTD, activity-dependent stabilization, BDNF-mediated plasticity	Potential for strong recovery, but risk of disrupted development if injury is severe or early	Injury during critical developmental windows, diffuse brain injury, and severity of TBI
Adults	Moderate, declining with age	Compensatory reorganization, LTP-dependent plasticity, limited neurogenesis, glial responses	Partial recovery via rerouting and compenzation	Excitotoxicity, inflammation, demyelination, and slower synaptic remodelling
Elderly	low	Reduced LTP, increased LTD, neurotransmitter decline (dopamine, acetylcholine, glutamate), reduced cerebral reserve	Poorer recovery, higher mortality even in mild cases of mortality	Brain atrophy, vascular fragility, reduced synaptic efficiency, and comorbidities

For example, in children and adolescents, there should be family involvement, cognitive training, and school reintegration programmes that help to restore learning and social skills. Adults may benefit more from task-specific rehabilitation such as physical therapy, occupational therapy, and cognitive rehabilitation aimed at improving independence and making it easier to return to work. In the elderly, rehabilitation should focus on balance training, fall prevention, and management

of existing medical conditions to account for their reduced neuroplasticity and slower recovery. These differences between age groups suggest that rehabilitation should be tailored to patients' age and stage of brain development.

8. Strengths and Limitations

A key strength of this review is its holistic and integrative scope. By synthesising evidence across molecular and cellular levels of analysis in 4 different age groups, this review provides a comprehensive framework for understanding age-dependent neuroplasticity after TBI. The inclusion of both human and animal studies strengthens the mechanistic explanations offered in the paper.

However, the limitations must be acknowledged. The review is narrative rather than systematic, so the search and selection process is not entirely replicable, introducing the possibility of selection bias. Second, much of the mechanistic evidence, such as evidence regarding LTP, LTD, and BDNF, is drawn from animal models (primarily rodents), which may not fully represent human neurophysiology. Additionally, only a few of the studies compared neuroplastic outcomes across all 4 age groups under controlled conditions. This means that the cross-group comparisons are inferential rather than directly evidenced.

9. Conclusion

Overall, neuroplasticity provides an important biological framework for recovery after TBI; however, both the developmental stage and severity of the injury influence the extent to which functional recovery occurs. While these neuroplastic mechanisms operate throughout the lifespan, much of the existing evidence reflects age-related differences in functional outcomes, which are likely influenced by, rather than direct measures of, underlying neuroplastic processes (Su et al., 2016). Younger individuals show greater baseline plasticity, but this does not always lead to better recovery. Early disruptions can interfere with important development processes (Anderson et al., 2005; Mulligan et al., 2022). Adults show moderate compensatory reorganization; and the elderly display the most limited neuroplastic capacity. These age-related differences have meaningful implications for clinical practice, particularly in rehabilitation. Future research should, therefore, prioritize age-specific longitudinal studies, greater inclusion of elderly populations, and the development of targeted therapeutic strategies using neuroplastic mechanisms at every stage of life.

10. References

Amlerova, Z., Chmelova, M., Anderova, M., & Vargova, L. (2024). Reactive gliosis in traumatic brain injury: A comprehensive review. *Frontiers in Cellular Neuroscience*, 18, 1335849. https://doi.org/10.3389/fncel.2024.1335849

Anderson, V., Catroppa, C., Morse, S., Haritou, F., & Rosenfeld, J. (2005). Functional Plasticity or Vulnerability After Early Brain Injury? *Pediatrics*, 116(6), 1374–1382. https://doi.org/10.1542/peds.2004-1728

Bear, M. F., & Malenka, R. C. (1994). Synaptic plasticity: LTP and LTD. *Current Opinion in Neurobiology*, 4(3), 389–399. https://doi.org/10.1016/0959-4388(94)90101-5

Bliss, T. V. P., & Cooke, S. F. (2011). Long-term potentiation and long-term depression: A clinical perspective. *Clinics*, *66 Suppl* 1(Suppl 1), 3–17. https://doi.org/10.1590/s1807-59322011001300002

Brady, S. P., Bolnick, D. I., Angert, A. L., Gonzalez, A., Barrett, R. D. H., Crispo, E., Derry, A. M., Eckert, C. G., Fraser, D. J., Fussmann, G. F., Guichard, F., Lamy, T., McAdam, A. G., Newman, A. E. M., Paccard, A., Rolshausen, G., Simons, A. M., & Hendry, A. P. (2019). Causes of maladaptation. *Evolutionary Applications*, *12*(7), 1229–1242. https://doi.org/10.1111/eva.12844

Burda, J. E., & Sofroniew, M. V. (2014). Reactive Gliosis and the Multicellular Response to CNS Damage and Disease. *Neuron*, *81*(2), 229–248. https://doi.org/10.1016/j.neuron.2013.12.034

Burke, S. N., & Barnes, C. A. (2006). Neural plasticity in the ageing brain. *Nature Reviews Neuroscience*, *7*(1), 30–40. https://doi.org/10.1038/nrn1809

Catharine, V. L., Helena, V., Ellen, D., Guy, V., Karel, D., & Karen, C. (2019). Exploration of gray matter correlates of cognitive training benefit in adolescents with chronic traumatic brain injury. *NeuroImage: Clinical*, *23*, 101827. https://doi.org/10.1016/j.nicl.2019.101827

Chan, A., Ouyang, J., Nguyen, K., Jones, A., Basso, S., & Karasik, R. (2024). Traumatic brain injuries: A neuropsychological review. *Frontiers in Behavioral Neuroscience*, *18*, 1326115. https://doi.org/10.3389/fnbeh.2024.1326115

Chaudhury, S., Sharma, V., Kumar, V., Nag, T. C., & Wadhwa, S. (2016). Activity-dependent synaptic plasticity modulates the critical phase of brain development. *Brain and Development*, *38*(4), 355–363. https://doi.org/10.1016/j.braindev.2015.10.008

Deoni, S. C. L., Dean, D. C., Remer, J., Dirks, H., & O'Muircheartaigh, J. (2015). Cortical maturation and myelination in healthy toddlers and young children. *NeuroImage*, *115*, 147–161. https://doi.org/10.1016/j.neuroimage.2015.04.058

Department of Neurosurgery, Hospital Sungai Buloh, Selangor, Malaysia, Othman, A., Idris, Z., Department of Neurosciences, School of Medical Sciences, Universiti Sains Malaysia, Kelantan, Malaysia, Rosman, A. K., Department of Neurosurgery, Hospital Sungai Buloh, Selangor, Malaysia, Abdullah, J. M., Department of Neurosciences, School of Medical Sciences, Universiti Sains Malaysia, Kelantan, Malaysia, Brain and Behaviour Cluster, School of Medical Sciences, Universiti Sains Malaysia, Kelantan, Malaysia, Ghani, A. R. I., Department of Neurosciences, School of Medical Sciences, Universiti Sains Malaysia, Kelantan, Malaysia, Zakaria, A. Z., & Department of Psychiatry, Hospital Sungai Buloh, Selangor, Malaysia. (2022). Cognitive Impairment and Neuropsychiatry Manifestation Following Mild and Moderate Traumatic Brain Injury at 3 Months and 6 Months. *Malaysian Journal of Medical Sciences*, *29*(5), 48–58. https://doi.org/10.21315/mjms2022.29.5.6

Dzyubenko, E., & Hermann, D. M. (2023). Role of glia and extracellular matrix in controlling neuroplasticity in the central nervous system. *Seminars in Immunopathology*, *45*(3), 377–387. https://doi.org/10.1007/s00281-023-00989-1

Fox, S. E., Levitt, P., & Nelson, C. A. (2010). How the Timing and Quality of Early Experiences Influence the Development of Brain Architecture. *Child Development*, *81*(1), 28–40. https://doi.org/10.1111/j.1467-8624.2009.01380.x

Giza, C. C., & Prins, M. L. (2006). Is being plastic fantastic? Mechanisms of altered plasticity after developmental traumatic brain injury. *Developmental Neuroscience*, *28*(4–5), 364–379. https://doi.org/10.1159/000094163

Gong, D., Zhang, S., Liu, L., Dong, J., Guo, X., Hao, M., Tu, Y., Diao, Y., & Zhang, J. (2011). Dynamic changes of vascular endothelial growth factor and angiopoietin-1 in association with circulating endothelial progenitor cells after severe traumatic brain injury. *The Journal of Trauma*, 70(6), 1480–1484. https://doi.org/10.1097/TA.0b013e31821ac9e1

Gustafsson, D., Klang, A., Thams, S., & Rostami, E. (2021). The Role of BDNF in Experimental and Clinical Traumatic Brain Injury. *International Journal of Molecular Sciences*, 22(7), 3582. https://doi.org/10.3390/ijms22073582

Johnson, B. P., & Cohen, L. G. (2022). Reward and plasticity: Implications for neurorehabilitation. *Handbook of Clinical Neurology*, 184, 331–340. https://doi.org/10.1016/B978-0-12-819410-2.00018-7

Johnson, K. E., & Wilgus, T. A. (2014). Vascular Endothelial Growth Factor and Angiogenesis in the Regulation of Cutaneous Wound Repair. *Advances in Wound Care*, 3(10), 647–661. https://doi.org/10.1089/wound.2013.0517

Johnston, M. V., Ishida, A., Ishida, W. N., Matsushita, H. B., Nishimura, A., & Tsuji, M. (2009). Plasticity and injury in the developing brain. *Brain & Development*, 31(1), 1–10. https://doi.org/10.1016/j.braindev.2008.03.014

Joseph, L., Mpolya, E. A., & Vianney, J.-M. (2023). Prevalence and risk factors of brain atrophy and associated confusion state among adults from three hospitals in northern Tanzania. *Pan African Medical Journal*, 45. https://doi.org/10.11604/pamj.2023.45.1.36831

Karve, I. P., Taylor, J. M., & Crack, P. J. (2016). The contribution of astrocytes and microglia to traumatic brain injury. *British Journal of Pharmacology*, 173(4), 692–702. https://doi.org/10.1111/bph.13125

Klein, M. O., Battagello, D. S., Cardoso, A. R., Hauser, D. N., Bittencourt, J. C., & Correa, R. G. (2019). Dopamine: Functions, Signaling, and Association with Neurological Diseases. *Cellular and Molecular Neurobiology*, 39(1), 31–59. https://doi.org/10.1007/s10571-018-0632-3

Kolstø, T., Werner, D., Thorsen, K., & Weber, C. (2025). Pediatric moderate and severe traumatic brain injury – A national, population-based cohort study. *European Journal of Trauma and Emergency Surgery*, 51(1), 324. https://doi.org/10.1007/s00068-025-02960-1

Kumar, A. (2011). Long-Term Potentiation at CA3–CA1 Hippocampal Synapses with Special Emphasis on Aging, Disease, and Stress. *Frontiers in Aging Neuroscience*, 3. https://doi.org/10.3389/fnagi.2011.00007

Maas, A. I. R., Menon, D. K., Adelson, P. D., Andelic, N., Bell, M. J., Belli, A., Bragge, P., Brazinova, A., Büki, A., Chesnut, R. M., Citerio, G., Coburn, M., Cooper, D. J., Crowder, A. T., Czeiter, E., Czosnyka, M., Diaz-Arrastia, R., Dreier, J. P., Duhaime, A.-C., … Zumbo, F. (2017). Traumatic brain injury: Integrated approaches to improve prevention, clinical care, and research. *The Lancet Neurology*, 16(12), 987–1048. https://doi.org/10.1016/S1474-4422(17)30371-X

Manley, G. T., & Maas, A. I. R. (2013). Traumatic Brain Injury: An International Knowledge-Based Approach. JAMA, 310(5), 473. https://doi.org/10.1001/jama.2013.169158

Maristany, A. J., Sa, B. C., Murray, C., Subramaniam, A. B., & Oldak, S. E. (2024). Psychiatric Manifestations of Neurological Diseases: A Narrative Review. *Cureus*, 16(7), e64152. https://doi.org/10.7759/cureus.64152

Mohammed, H., & Hollis, E. R. (2018). Cortical Reorganization of Sensorimotor Systems and the Role of Intracortical Circuits After Spinal Cord Injury. *Neurotherapeutics*, 15(3), 588–603. https://doi.org/10.1007/s13311-018-0638-z

Mulligan, T., Barker-Collo, S., Gibson, K., & Jones, K. (2022). You Only Get One Brain: Adult Reflections on the Long-Term Impacts of Traumatic Brain Injury in Adolescence. *Brain Impairment*, 23(3), 278–295. https://doi.org/10.1017/BrImp.2021.22

Nahmani, M., & Turrigiano, G. G. (2014). Adult cortical plasticity following injury: Recapitulation of critical period mechanisms? *Neuroscience*, 283, 4–16. https://doi.org/10.1016/j.neuroscience.2014.04.029

Olsen, M., Vik, A., Lien, E., Schirmer-Mikalsen, K., Fredriksli, O., Follestad, T., Sandrød, O., Finnanger, T. G., & Skandsen, T. (2022). A population-based study of global outcome after moderate to severe traumatic brain injury in children and adolescents. *Journal of Neurosurgery: Pediatrics*, 29(4), 397–406. https://doi.org/10.3171/2021.11.PEDS21285

Prasad, G. L., Anmol, N., & Menon, G. R. (2018). Outcome of Traumatic Brain Injury in the Elderly Population: A Tertiary Center Experience in a Developing Country. *World Neurosurgery*, 111, e228–e234. https://doi.org/10.1016/j.wneu.2017.12.034

Pruitt, D. T., Danaphongse, T. T., Schmid, A. N., Morrison, R. A., Kilgard, M. P., Rennaker, R. L., & Hays, S. A. (2017). Traumatic Brain Injury Occludes Training-Dependent Cortical Reorganization in the Contralesional Hemisphere. *Journal of Neurotrauma*, 34(17), 2495–2503. https://doi.org/10.1089/neu.2016.4796

Puderbaugh, M., & Emmady, P. D. (2025). Neuroplasticity. In *StatPearls*. StatPearls Publishing. http://www.ncbi.nlm.nih.gov/books/NBK557811/

Race, N. S., Moschonas, E. H., Kline, A. E., & Bondi, C. O. (2024). Cognition and Behavior in the Aging Brain Following TBI: Surveying the Preclinical Evidence. In L. J. Noble-Haeusslein & D. M. Schnyer (Eds), *Traumatic Brain Injuries* (Vol. 42, pp. 219–240). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-69832-3_11

Rajan, R. K. (2025). A comprehensive review on adaptive plasticity and recovery mechanisms post-acquired brain injury. *Neuroprotection*, 3(3), 226–252. https://doi.org/10.1002/nep3.70006

Ridderinkhof, K. R., & Krugers, H. J. (2022). Horizons in Human Aging Neuroscience: From Normal Neural Aging to Mental (Fr)Agility. *Frontiers in Human Neuroscience*, 16, 815759. https://doi.org/10.3389/fnhum.2022.815759

Sakai, J. (2020). Core Concept: How synaptic pruning shapes neural wiring during development and, possibly, in disease. *Proceedings of the National Academy of Sciences of the United States of America*, 117(28), 16096–16099. https://doi.org/10.1073/pnas.2010281117

Schliebs, R., & Arendt, T. (2011). The cholinergic system in aging and neuronal degeneration. *Behavioural Brain Research*, 221(2), 555–563. https://doi.org/10.1016/j.bbr.2010.11.058

Sikora, E., Bielak-Zmijewska, A., Dudkowska, M., Krzystyniak, A., Mosieniak, G., Wesierska, M., & Wlodarczyk, J. (2021). Cellular Senescence in Brain Aging. *Frontiers in Aging Neuroscience*, 13, 646924. https://doi.org/10.3389/fnagi.2021.646924

Sophie Su, Y., Veeravagu, A., & Grant, G. (2016). Neuroplasticity after Traumatic Brain Injury. In D. Laskowitz & G. Grant (Eds), *Translational Research in Traumatic Brain Injury*. CRC Press/Taylor and Francis Group. http://www.ncbi.nlm.nih.gov/books/NBK326735/

Swerlick, R. A. (1995). Angiogenesis. *The Journal of Dermatology*, 22(11), 845–852. https://doi.org/10.1111/j.1346-8138.1995.tb03934.x

Tan, L. T. P., Lim, C. Y. J., Koh, J. H., Chandran, G., Tan, L. F., & Merchant, R. A. (2025). Functional recovery in older adults following mild traumatic brain injury: A systematic review. *European Geriatric Medicine*. https://doi.org/10.1007/s41999-025-01326-5

Thompson, H. J., Rivara, F. P., & Wang, J. (2020). Effect of Age on Longitudinal Changes in Symptoms, Function, and Outcome in the First Year After Mild-Moderate Traumatic Brain Injury. *Journal of Neuroscience Nursing*, 52(2), 46–52. https://doi.org/10.1097/JNN.0000000000000498

Treble-Barna, A., Zang, H., Zhang, N., Taylor, H. G., Yeates, K. O., & Wade, S. (2017). Long-Term Neuropsychological Profiles and Their Role as Mediators of Adaptive Functioning after Traumatic Brain Injury in Early Childhood. *Journal of Neurotrauma*, 34(2), 353–362. https://doi.org/10.1089/neu.2016.4476

Utomo, W. K., Gabbe, B. J., Simpson, P. M., & Cameron, P. A. (2009). Predictors of in-hospital mortality and 6-month functional outcomes in older adults after moderate to severe traumatic brain injury. *Injury*, 40(9), 973–977. https://doi.org/10.1016/j.injury.2009.05.034

Wang, H., Song, G., Chuang, H., Chiu, C., Abdelmaksoud, A., Ye, Y., & Zhao, L. (2018). Portrait of glial scar in neurological diseases. *International Journal of Immunopathology and Pharmacology*, 31, 2058738418801406. https://doi.org/10.1177/2058738418801406

Wei, H., Jiang, R., Liu, L., & Zhang, J. (2010). Circulating endothelial progenitor cells in traumatic brain injury: An emerging therapeutic target? *Chinese Journal of Traumatology = Zhonghua Chuang Shang Za Zhi*, 13(5), 316–318. https://pubmed.ncbi.nlm.nih.gov/20880461/

Weston, N. M., Rolfe, A. T., Freelin, A. H., Reeves, T. M., & Sun, D. (2021). Traumatic brain injury modifies synaptic plasticity in newly-generated granule cells of the adult hippocampus. *Experimental Neurology*, 336, 113527. https://doi.org/10.1016/j.expneurol.2020.113527

Wilkins, T. E., Beers, S. R., Borrasso, A. J., Brooks, J., Mesley, M., Puffer, R., Chang, Y.-F., Okonkwo, D. O., & Puccio, A. M. (2019). Favorable Functional Recovery in Severe Traumatic Brain Injury Survivors beyond Six Months. *Journal of Neurotrauma*, 36(22), 3158–3163. https://doi.org/10.1089/neu.2018.6153

Winter, L., Mensinger, J. L., Moriarty, H. J., Robinson, K. M., McKay, M., & Leiby, B. E. (2022). Age Moderates the Effect of Injury Severity on Functional Trajectories in Traumatic Brain Injury: A Study Using the NIDILRR Traumatic Brain Injury Model Systems National Dataset. *Journal of Clinical Medicine*, 11(9), 2477. https://doi.org/10.3390/jcm11092477

Wong, L., Chong, Y. S., Lin, W., Kisiswa, L., Sim, E., Ibáñez, C. F., & Sajikumar, S. (2021). Age-related changes in hippocampal-dependent synaptic plasticity and memory mediated by p75 neurotrophin receptor. *Aging Cell*, 20(2), e13305. https://doi.org/10.1111/acel.13305

Zamani, A., Ryan, N. P., Wright, D. K., Caeyenberghs, K., & Semple, B. D. (2020). The Impact of Traumatic Injury to the Immature Human Brain: A Scoping Review with Insights from Advanced Structural Neuroimaging. *Journal of Neurotrauma*, 37(5), 724–738. https://doi.org/10.1089/neu.2019.6895

Zhou, Y., & Danbolt, N. C. (2014). Glutamate as a neurotransmitter in the healthy brain. *Journal of Neural Transmission*, 121(8), 799–817. https://doi.org/10.1007/s00702-014-1180-8

Zotey, V., Andhale, A., Shegekar, T., & Juganavar, A. (2023). Adaptive Neuroplasticity in Brain Injury Recovery: Strategies and Insights. *Cureus*. https://doi.org/10.7759/cureus.45873

Acknowledgements

The author would like to express her sincere gratitude to **Dr. Kimberly Clark** and **Ms. Monika Rybak** for their invaluable guidance, expertise, and continuous support.

Author Biography

Jagriti Khare is a high school student at Dover Court International School in Singapore with a strong interest in neuroscience, medicine, and scientific research. She is currently doing the International Baccalaureate Diploma Programme (IBDP) at school and has taken subjects such as biology, chemistry, and psychology at higher level. These have further developed her interests in understanding the biological and psychological mechanisms underlying human health. Through this literature review, she explores age-related differences in neuroplasticity following traumatic brain injury, while developing skills in scientific writing.

In addition to academics, she is the co-founder of her school's Medicine Club and has gained clinical exposure through an internship at a physician's clinic. She has pursued her interest in neuroscience by attending the Columbia University Summer program in neuroscience, where she explored brain function and cognition. She is also passionate about promoting body positivity and raising awareness about the impacts of body shaming on the mental health of teenagers through a campaign titled "Beauty from the Inside," where she researched and gave a presentation to village girls in India. Jagriti is also doing an online work experience and understanding the professional world in medicine by learning about networking skills and teamwork. She is working on building her profile to pursue a career in medicine and continue contributing to neuroscience research in the future.

Mentor Contribution Statement

Dr. Kimberly Clark was the primary academic mentor throughout the development of this research paper, providing consistent guidance on both the scientific content and the overall structure of the manuscript. Dr Clark played a major role in helping the author strengthen the quality of the paper by giving detailed feedback across many drafts and ensuring

that the content was scientifically accurate, organized, and supported by appropriate evidence. From her expertise in neuroscience, Dr Clark helped the author develop a deeper understanding of the concepts behind traumatic brain injury and neuroplasticity. She clarified difficult topics that arose during the research process, and her guidance enabled the author to present scientific literature more accurately and confidently. In addition to subject-specific guidance, Dr Clark introduced the author to citation software, which improved the organization of their work throughout the development of the manuscript. The author continues to use this software for other academic work, making it a very valuable skill gained.

Ms. Monika Rybak assisted the author in finding relevant academic sources, which helped to strengthen key sections of the paper. She provided advice on the structuring of the manuscript and ensuring the paper had a coherent narrative. Through regular office hours, the author was able to discuss progress and revisions and gain constructive feedback from Ms Monika Rybak. She helped the author approach revisions more systematically and develop stronger academic writing and research skills.