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The contribution of social determinants of health to long-term outcomes following traumatic brain injury

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ABSTRACT

Social Determinants of Health (SDoH) are a significant factor in health outcomes for both acute and chronic health conditions, but systematic research related to outcomes from traumatic brain injury (TBI) has been limited. This study explores the relationship between individual and neighborhood-level SDoH and TBI outcomes to understand the extent of their influence on long-term recovery. Hybrid panel models that decompose time-varying predictors into between- and within-person effects were used to examine the relationships between SDoH and participation in the community, life satisfaction, and global functioning for persons with moderate to severe TBI one to 30 years post-injury. Participants were 9263 persons, distributed nationally, who received inpatient rehabilitation for TBI and enrolled in the TBI Model Systems longitudinal study. Individual-level SDoH included sex, race/ethnicity, education, employment, insurance, primary means of transportation, and rurality. The Social Vulnerability Index (SVI) was used as an indicator of neighborhood disadvantage. Results indicated that neighborhood-level SDoH accounted for differences in outcomes between individuals but not due to change in a given individual's neighborhood. These findings were robust to the inclusion of numerous individual-level SDoH, which were also associated with the outcomes. Individual-level SDoH accounted for differences in outcomes both between individuals and with change in a given individual's status. Among four thematic subscales constituting the SVI, the socio-economic status subscale was consistently associated with all three outcomes.

1. Introduction

The Centers for Disease Control and Prevention estimates that over 200,000 hospitalizations for traumatic brain injury (TBI) occur annually in the U.S (Centers for Disease Control and Prevention, 2023) and almost 70,000 individuals die (Bell et al., 2017). In 2019, there were more than 27 million new cases of TBI globally, with approximately 50 million people living with disability due to these injuries (Guan et al., 2023). Longitudinal studies of the course of TBI indicate that it is a chronic health condition, and outcomes are more likely to be dynamic than stable (Brett et al., 2023; Dams-O'Connor et al., 2023). Many factors affect long-term outcomes including pre-injury health status and post-injury treatment and social circumstances (Dams-O'Connor et al., 2023). Among post-injury factors, the environment in which a person lives has been shown to affect health outcomes (National Academies of Sciences, Engineering, and Medicine, 2022), including, for example, the services and supports available in one's state (Corrigan et al., 2012; Corrigan et al., 2021). Social determinants of health (SDoH) are highly associated with health and well-being in the general population (Social Determinants of Health; Healthy People 2030 | Health.Gov, 2024) but have received limited attention in studies investigating long-term effects of TBI (National Academies of Sciences, Engineering, and Medicine, 2022). SDoH introduce risk factors that vary at the individual level (e.g., the person's socioeconomic position, race/ethnicity, or social support), as well as environmental level (e.g., their community's socioeconomic resources, housing, public safety, or the quality and availability of health and social services).

In TBI outcomes studies that have examined individual-level sources

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of SDoH, gender is commonly confounded with sex, but findings consistently demonstrate that females have worse global outcomes, more behavioral health problems, and lower return to work (Mikolić et al., 2021; Stein et al., 2019). Blacks, Hispanics, and Native Americans who experience TBI are reported to have higher rates of mortality (Bonow et al., 2018; G. F. Miller et al., 2021; Saadi et al., 2022), insomnia (Wickwire et al., 2016, 2022), poorer functional outcome (Arango-Lasprilla, Rosenthal, Deluca, Cifu, et al., 2007; Juengst et al., 2022), lower life satisfaction (Arango-Lasprilla et al., 2009; Perrin et al., 2014; Williamson et al., 2016), more behavioral health problems (Hart et al., 2016; Perrin et al., 2014), higher unemployment (Arango-Lasprilla et al., 2008; Cuthbert et al., 2015; Perrin et al., 2014), and less community participation (Hart et al., 2005; Kersey et al., 2019; Sander et al., 2009) when compared to non-Hispanic Whites. Higher mortality rates due to TBI have been found for people living in rural areas when compared to urban residents, which may be due to reduced access to immediate and appropriate trauma care; though, these findings may be confounded by injury severity (Daugherty, 2021; Daugherty et al., 2022). Rural versus urban difference in long-term outcomes have not been studied. One of the few studies evaluating long-term outcomes from TBI for those living in rural areas found that rural residents received fewer vocational services and were less likely to be employed post-injury than those living in urban areas (Johnstone et al., 2006). Socioeconomic status (SES) has also been found to be associated with outcomes, where persons with lower SES have greater risk for early mortality following discharge (Selassie et al., 2014), poorer global outcomes at one year (Singh et al., 2019), and increased risk for anxiety (Hart et al., 2016). Following TBI, patients who are uninsured are less likely than those with insurance to receive more than two interventional procedures, even when accounting for individuals with the most severe injuries (Missios & Bekelis, 2016). Uninsured patients were also more likely to have life supports withdrawn following severe TBI (Williamson et al., 2020).

Currently, only emerging evidence exists for the effect of neighborhood-level socioeconomic deprivation on TBI outcomes. In one study that used the Area Deprivation Index, persons from those areas scoring highest on deprivation had higher symptom acuity starting days post-injury and continuing for at least six months (Miller et al., 2023). A study in the United Kingdom found that those living in more socioeconomically deprived areas at the time of injury reported poorer global outcomes at 12 months post-injury (Humphries et al., 2020).

Most studies of the effects of SDoH on outcomes following TBI have focused on single factors or, at most, two SDoH. However, given the wide-ranging effects found to date, the experiences of members of marginalized groups who have incurred a TBI are likely complex and interacting. The goal of the current study was to consider both individual and neighborhood sources of SDoH associated with outcomes from TBI, with the inclusion of neighborhood SDoH (here, measured as the census tract), a novel contribution for TBI outcomes. Consistent with prior findings, we expected SDoH that are indicative of marginalized or disadvantaged social status to have negative effects on long-term outcomes, but that specific aspects of SDoH could affect outcomes differently. We chose to focus on high-level outcomes of community participation, life satisfaction, and global functioning to provide a general overview of the impact of SDoH. To better understand the potentially dynamic effects of SDoH, we used hybrid panel models that decompose SDoH into between- and within-person effects. While between-person effects provide the effects of average exposure over time, the within-person effects provide the opportunity to examine effects of changes in SDoH, whether neighborhood- or individual-level, on change in TBI outcomes.

2. Materials and methods

We linked individual-level longitudinal data with Census sociodemographic data using geographic identifiers to create a unique multilevel dataset, described below.

2.1. Individual-level data

Individual-level data came from the TBI Model Systems (TBIMS) National Database (TBIMS NDB). Created in 1987 by the (now) National Institute on Disability, Independent Living, and Rehabilitation Research (NIDILRR), TBIMS is a longitudinal, prospective study of the long-term health and well-being of people who received acute rehabilitation for a primary diagnosis of TBI (Dijkers et al., 2018). Sixteen centers are designated by NIDILRR as centers of excellence in TBI for 5-year funding cycles and 23 have contributed data to the TBIMS NDB since its inception. Over 20,000 participants have been enrolled who meet the following criteria at the time of injury: moderate to severe TBI as defined by Glasgow Coma Scale (GCS) score <13 on emergency admission, post-traumatic amnesia >24 h, or trauma-related intracranial abnormality on neuroimaging; age 16 years or older; presented to a designated TBIMS acute care hospital within 72 h of injury; and completed acute inpatient rehabilitation care within the TBIMS center. Acute rehabilitation is defined as including physical therapy, occupational therapy, speech therapy, rehabilitation psychology/neuropsychology, and/or family support/education in an integrated, team approach (Traumatic Brain Injury Model Systems Program, 2019). Demographic, pre-injury, and injury-related characteristics are gathered on rehabilitation inpatient admission for participants who are subsequently followed at 1-, 2-, and 5-years post-injury, and every 5 years thereafter. Follow-up data are collected primarily by telephone interview, but some participants may be interviewed in-person or complete a self-administered questionnaire that is returned by mail. While the TBIMS follow-up data collection relies extensively on self/proxy-report, almost all variables have shown high test/re-test reliability (Bogner et al., 2017). The TBIMS centers have maintained a follow-up rate greater than 80 % for all years of longitudinal monitoring (Dijkers et al., 2018).

The analytic sample used for this investigation included data from participants with follow-up interviews conducted from 2010 to 2022, which coincided with the time period when geographic identifiers were added to the TBIMS NDB (i.e., from 2010 to the present). The TBIMS data were pulled in December 2022. Using the outcome with most data points (GOS-E, see below), the analytic sample included 18,247 interviews across 9263 unique individuals. With 13 calendar years within the study timeframe, participants could have a maximum of four follow-up observations occurring up to 30 years post-injury, with a mean of 2.0 observations and 64.4 % of individuals contributing more than one observation. Supplemental Table 1 shows differences in baseline interview characteristics among those with one and multiple observations, which show considerable similarities.

2.2. Neighborhood disadvantage

Neighborhood disadvantage data came from the Centers for Disease Control and Prevention (CDC), which uses U.S. Census data to create the Social Vulnerability Index (SVI) (Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry/Geospatial ResearchAnalysisand Services Program, 2022). The SVI has been shown to be comparable to other area deprivation indices (Lou et al., 2023) and has more years of data available than other commonly used measures. The SVI uses a percentile ranking computed by scoring the vulnerability of each census tract relative to the entirety of the U.S. Factors comprising the SVI are also grouped into one of four subthemes (see Fig. 1): Socioeconomic Status; Household Composition; Housing Type/-Transportation; and Racial and Ethnic Minority Status. These subthemes are described below.

The CDC released data for 2010, 2014, 2016, 2018, and 2020. For decennial census years (i.e., 2010 and 2020), scores are based on questions obtained from the US Census. For other years, scores are based on American Community Survey data. To cover years in between SVI

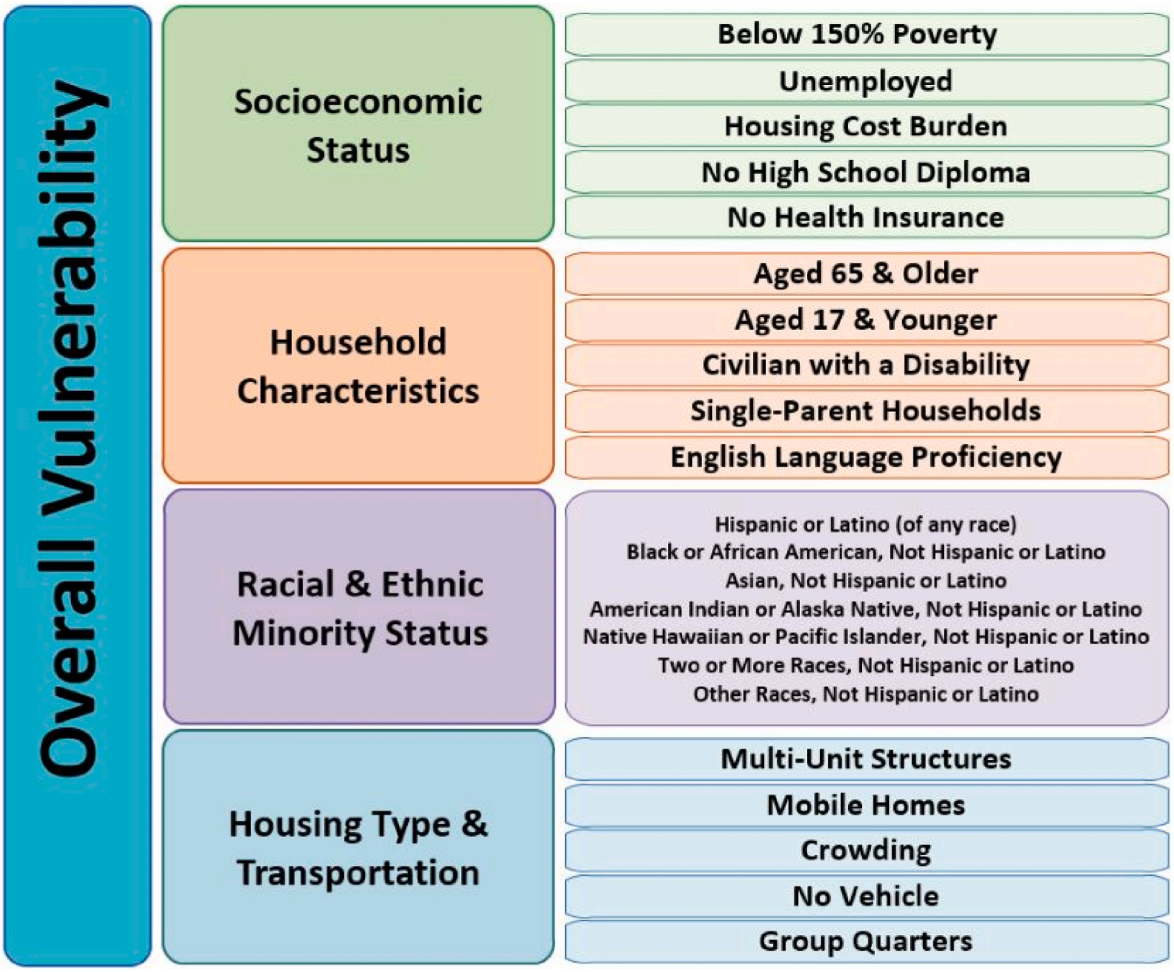

Fig. 1. Center for disease control and prevention social vulnerability index Subthemes (Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry/Geospatial ResearchAnalysisand Services Program, 2022).

data releases, we interpolated between years for which we had TBIMS NDB data available. The SVI data were pulled in December 2022. Because 2020 was the most recent data release, the numbers for 2021 and 2022 are held constant at the 2020 numbers, as no interpolation was possible.

Slight differences incurred over time in how SVI was computed. The number of component factors was 14 in 2010, 15 in 2014, 2016, and 2018, and 16 in 2020. Additionally, in 2020, the specific social factor, 'English language proficiency,' was moved from the Minority Status subtheme to Household Characteristics, leaving Minority Status as a measure of non-White households. With these changes, the total possible score of the index also changed. Thus, we standardized the scores at each year to account for variation in calculation methods. We also ran models before and after 2020, finding similar results to those presented below. Additionally, we tested an interaction between SVI and year, which was non-significant, indicating similar effects of SVI by year. Each of these approaches reduces concerns about effects due to changes in the SVI measure, as well as any potential effect of the COVID pandemic.

As of the 2020 Census, there were 84,414 census tracts in the U.S. (United States Census Bureau, 2022). Using 2020 as an example, 1912 of these census tracts are represented among respondents in the TBIMS NDB. Given the relatively small sample size of the TBIMS NDB, nesting of multiple people within the same tract was relatively uncommon, averaging 3.66 observations per tract (SD = 2.82). In the sample, 47.36 % of tracts had only one observation and 90.49 % had four or fewer observations. The census tract with the most observations had 23, followed by 19 observations.

2.2.1. Measures

2.2.1.1. Individual-level predictors. Time-invariant, individual-level indices of SDoH were race/ethnicity (categories White non-Hispanic (referent group first), Black non-Hispanic, Asian/Pacific Islander, Hispanic, Other), sex (female, male), and type of insurance at time of injury (Medicare, Medicaid, private, other). Time-varying SDoH (i.e., those measured at each follow-up) included education level (high school or less, some college, bachelor's degree or more), employment status (not employed, employed), transportation mode used most of the time (driving own vehicle, riding with someone else, relying on public transit, using a special bus/van), and urbanicity (rural, suburban, urban).

We also included additional covariates shown to have an association with the outcomes of investigation. Time-invariant covariates were age at injury, pre-injury at-risk use of substances (no, yes), cause of injury (vehicular, violence, sports, fall, hit by object, other), days from injury to following verbal commands, Functional Independence Measure (FIM™) Motor scores at rehabilitation admission and discharge (after October 2019, derived from CARETool scores using a validated crosswalk (Mellick et al. 2025)), and residence after rehabilitation discharge (private house, location other than private house (Traumatic Brain Injury Model Systems Program, 2019). Time-varying covariates were FIM™ Motor and Cognitive scores at follow-up, marital status (single, married, divorced/separated/widowed), and living situation (alone, spouse/significant other, other family, any other living arrangement (Traumatic Brain Injury Model Systems Program, 2019). Finally, to model time, we included years post-injury at follow-up (continuous) and

year of injury (coded in half decades). We also included a time-varying dummy variable for whether the respondent moved to a different census tract since their previous observation, described below.

2.2.1.2. Social Vulnerability Index. We used the SVI Total score and the four SVI subthemes. As recommended by CDC, for each of the four subthemes, we summed the percentiles for the variables comprising each theme. We then ordered the summed percentiles for each theme to determine theme-specific percentile rankings (Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry/Geospatial ResearchAnalysisand Services Program, 2022). The SVI Total score represents the overall vulnerability of a tract calculated as the sum of the percentile rankings of the proportion of persons or households that meet the criteria for each of the social factors. To create these percentiles, CDC "… summed the sums for each theme, ordered the tracts, and then calculated overall percentile rankings" (Centers for Disease Control and Prevention/Agency for Toxic Substances and Disease Registry/Geospatial Research, Analysis, and Services Program, 2022). As described above, because the categories are made up of different variables across years, we standardized these ranks for modeling purposes. Since we standardized overall SVI and each subtheme, the coefficients can be interpreted as reflecting the effect on the outcome of a one standard deviation increase in disadvantage as operationalized by the index.

2.2.1.3. Outcome measures. We examined three individual-level outcomes: (1) participation in the community, (2) global functioning, and (3) life satisfaction. Community participation was assessed using the Participation Assessment with Recombined Tools-Objective (PART-O) total score (Bogner et al., 2011; Whiteneck et al., 2011), with higher scores indicating more frequent community participation. The PART-O has excellent test-retest reliability (Bogner et al., 2017), and construct validity has been established using rating scale analysis (Bogner et al., 2011, 2017; Whiteneck et al., 2011). PART-O scores were converted to a linear metric with equal intervals using Rasch analysis. While there is some loss of sample size due to needing values for all items (n = 11,839; 34 %), the resulting scale has superior psychometric properties (Malec et al., 2016).

Global functioning was based on ratings from the Glasgow Outcome Scale–Extended (GOS-E (Wilson et al., 1998)), which was developed to address the limitations of the original Glasgow Outcome Scale. For this analysis, we used three levels of the GOS-E: severe disability (including vegetative state), moderate disability (i.e., unable to resume 50 % of previous activities and social roles), and good recovery (i.e., resumption of 50 % of activities and roles even though some impairments persist). Higher scores indicate a better outcome. Use of a structured interview for elicitation allows appropriate interrater and test-retest reliability (Bogner et al., 2017; R. H. Wilson & McArdle, 2020).

Life satisfaction was measured using the Satisfaction With Life Scale (SWLS (Diener et al., 1985; Pavot et al., 1991), which consists of five items designed to elicit a respondent's subjective sense of well-being, with higher scores representing greater satisfaction. Reliability, criterion-related validity, and construct validity have been well-established through its 35-year history with multiple populations, including persons with TBI.

2.2.2. Analytic strategy

We used hybrid panel models that decompose time-varying predictors into between- and within-person effects. The structure of the data was repeated observations (Level 1) nested in each individual (Level 2). Time-varying measures were located at Level 1 as within-person effects. They were coded as deviations from the person-specific average for that variable. These within-person effects assessed whether changes in time-varying predictors were associated with changes in the outcome. This approach was a major strength of the modeling as change cannot be biased by static characteristics, either measurable or unmeasurable, of the individual. For example, it assessed whether changes in an individual's SVI Total score affected their value on the outcome relative to observations with lower SVI scores. Note that in this case, the individual experienced a change in exposure (i.e., SVI), which was the value of the within-person effects. Table 1 includes the percentage of within-person variation on time-varying predictors and the outcomes, whose values lend confidence that null within-person findings are not solely due to lack of within-person variation.

In addition to stable individual-level predictors (e.g., race, sex), Level 2 models between-person effects measured as person-specific averages across all observations of time-varying predictors. The between-person coefficient thus represented average differences across individuals. For example, it assessed whether someone one unit higher on SVI, on average, had higher values on the outcomes relative to someone one unit lower on average SVI. Note that in this case, the difference between the two individuals is the average SVI over the whole period, which is the value of the between-person effects.

Using Stata's xthybrid procedure, we ran four nested models for each of our three outcomes. All models included SVI, but then we subsequently included additional predictors. Model 1 included only calendar year of follow-up interview and year of injury. Model 2 added the characteristics of the individual that did not change from year to year. Model 3 added the time-varying predictors as both between and within effects. Finally, Model 4 added only a dummy variable indicating whether the individual had moved across census tracts since their last observation, which allowed us to determine if a change in results was predominately due to moving. We repeated this modeling strategy across each of the four subtheme scores. The Variance Inflation Factor was within acceptable limits, indicating no issues with collinearity. Since our analytic unit of interest centered on the individual, we could not adjust for those individuals contained within the same geographic unit. However, as noted above, for nearly half the sample, there was only one observation in a tract, and few individuals shared the same tracts.

3. Results

3.1. Descriptive statistics

Participant characteristics are reported in Table 1, pooled over observations. Though the analytical sample size varied slightly across outcomes due to missing observations, the sample composition remained relatively consistent across outcomes. For ease of presentation, Table 1 reports the characteristics for all cases based on the global disability outcome (measured by the GOS-E). Supplemental Table 2 includes demographics of the SWLS and PART-O models, respectively. The demographic composition of this sample is consistent with the overall TBIMS cohort.

The majority (73 %) of participants were male. Their average age at injury was 40.94 years, ranging between 16 and 99. The largest racial category was White non-Hispanic, representing 70 % of individuals. About 43 % of respondents lived with a spouse or significant other, while 39 %, were single. In the analytic sample, 44 % of respondents had a high school education or less, and 62 % were not employed. Of all respondents, 53 % used their own car as their primary mode of transportation. Less than half, 41 % of respondents, reported risky substance use. The highest concentration of respondents (43 %) lived in urban areas. Of the sample, 13 % moved during data collection. The most common cause of injury was vehicular crash at 52 %. At the time of injury, 45 % of respondents had private health insurance.

Social Vulnerability Index predictors were standardized to have a mean of zero and standard deviation of 1 when considering all census tracts across the entire country. Once merged into the individual-level dataset, these values were no longer exactly 1 and 0, respectively, but remained close.

The mean PART-O Rasch score was 56.61 with a standard deviation

Table 1
Sample characteristics TBI Model Systems National Database participants from 2010 to 2022 (Sample for GOS-E).

Variable (sample for GOS-E)	Mean (S.D.) or %	Percentage of variation within individual
Dependent Variables		
Part Rasch (n = 12,767)	56.61 (6.56)	15.8 %
SWLS (n = 14,989)	22.27 (8.20)	17.0 %
GOS-E (n = 18,243)	5.98 (1.71)	15.9 %
Independent Variables		
Standardized SVI Themes Total	−0.04 (1.01)	11.7 %
Standardized SVI Socioeconomic Status	−0.08 (1.03)	11.2 %
Standardized SVI Household Composition	−0.05 (1.00)	17.6 %
Standardized SVI Housing Type	−0.02 (1.00)	16.7 %
Standardized SVI Minority Status	0.09 (0.96)	10.2 %
Covariates		
Male	72.81 %	
Age	40.94 (18.80)	
Race		
White non-Hispanic	69.26 %	
Black non-Hispanic	15.46 %	
Asian/Pacific Islander	2.61 %	
Hispanic	10.99 %	
Other	1.68 %	
Marital Status		
Single	38.97 %	(baseline)
Married	36.38 %	10.0 %
Divorced/Separated/ Widowed	24.53 %	8.6 %
Other	0.12 %	34.7 %
Living Situation at time of interview		
Alone	16.01 %	(baseline)
Spouse or significant other	43.23 %	13.8 %
Other family	33.14 %	17.3 %
Someone else	7.62 %	21.7 %
Educational Attainment		
HS or less	43.99 %	(baseline)
Some college	31.36 %	9.1 %
Bachelor's or higher	24.65 %	4.6 %
Employed full time	38.02 %	18.8 %
Primary mode of transportation		
Drives vehicle	52.91 %	(baseline)
Rides with someone else	34.94 %	20.3 %
Public transit	8.97 %	21.3 %
Special bus/van	3.18 %	21.5 %
Risk of substance use	41.00 %	
Rurality		
Rural	24.85 %	
Urban	42.32 %	
Suburban	32.82 %	
Moved during study	13.07 %	60.5 %
Cause of Injury		
Vehicular	52.43 %	
Violence	9.15 %	
Sports	2.74 %	
Fall	26.68 %	
Hit by object	1.35 %	
Other	7.65 %	
Time to following commands in days	7.28 (12.90)	
FIM Motor Score at admission	36.05 (17.51)	
FIM Motor Score at discharge	67.55 (16.70)	
FIM Motor Score at follow up	84.88 (12.22)	8.3 %
FIM Cognition Score at follow up	31.27 (4.46)	13.0 %
Private residence at discharge	85.14 %	
Primary rehabilitation payor		
Medicare	12.43 %	
Medicaid	18.62 %	
Private	46.44 %	
Other	22.51 %	
Years to follow up	4.48 (4.86)	19.7 %

GOS-E = Glasgow Outcome Scale–Extended, SWLS = Satisfaction With Life Scale, SVI = Social Vulnerability Index, HS = high school, FIM = Functional Independence Measure. Within-person variability for categorical time-varying predictors is relative to changes to the baseline categories.

of 6.56. The SWLS averaged 22.27 with a standard deviation of 8.20. The GOS-E had an average score of 5.98 and a standard deviation of 1.71.

3.2. Modeling using SVI total score

Table 2 displays a series of nested models that shows only the between- and within-person coefficient for Total SVI—the full model with all covariates is in Supplemental Tables 3–17. Across all three outcomes, we found no within-person effects, but significant between-person effects emerged. For a given individual, a change in their SVI did not result in a change in the outcomes; however, comparing across individuals, differences in average SVI were associated with all three outcomes. Those with lower SVI Total scores had better outcomes. The inclusion of other predictors across the nested models decreased the magnitude of the SVI effect for all three outcomes.

For community participation as measured by the PART-O Rasch, Model 1 includes only change over time. The significant between-effect represents the effect for two individuals separated by one standard deviation in average SVI across all observations. This one standard deviation increase in SVI was associated with a 1.14 unit decrease in PART-O score ($p < 0.001$). Model 2 added time-invariant measures (e.g., race/ethnicity, sex), and the relationship between SVI and community participation was attenuated (i.e., a one standard deviation increase in SVI was associated with an average decrease of 0.82 units in PART-O ($p < 0.001$)). Model 3 adjusted for the between- and within-effects of individual-level time-varying measures (e.g., education, transportation access, employment) further reducing the SVI coefficient to 0.27 ($p < 0.001$). Finally, in the fourth model which considered the effect of moving, a one standard deviation increase in SVI was associated with a 0.27 unit decrease in PART-O ($p < 0.001$).

We found a similar pattern for global outcome on the GOS-E across the nested models. In Model 1, a one standard deviation increase in SVI was associated with an average decrease of 0.25 units in the GOS-E ($p < 0.001$). Over the same four models, the effect was only a decrease of 0.028, but again was still significant ($p < 0.05$). By contrast, while a one standard deviation increase in SVI was associated with a 1.11 unit decrease in life satisfaction in the first model, this difference was fully accounted for after adjusting for the time-varying and invariant covariates in subsequent models.

The effects of the individual-level variables were consistent across the models for a given outcome (see Table 2); thus, the fully adjusted model (Model 4) shown in Table 3 and depicted in coefficient plots in Fig. 2 demonstrate the contributions of these variables. For explanatory purposes we describe here only the results for community participation. Black non-Hispanic respondents reported more community participation with scores 0.36 units higher ($p < 0.001$) than scores for White non-Hispanic respondents. In contrast, Asian/Pacific Islander participants' scores were 1.32 units lower ($p < 0.001$) than those for White non-Hispanics. For insurance status at injury, having Medicaid was the only insurance category shown to have a significant negative effect on community participation, with a PART-O score 0.71 units lower relative to Medicare ($p < 0.05$). There were no differences in community participation between men and women.

Variables that varied over time were examined for within-person (effects of a change for a given individual) and between-person (effects for average differences among individuals) effects. Educational status was significant in predicting community participation for those with some college or higher when compared between individuals (not as individuals gained more education). Those with some college education were on average 1.11 units higher on community participation, and those with a bachelor's degree or higher were an average 1.93 units higher than those with high school or less education ($p < 0.001$). Employment and transportation both showed significant effects within and between individuals. For the within-effect, being employed at a given point in time was associated with community participation—the

Table 2
Unadjusted and adjusted nested mixed effects models predicting community participation, satisfaction with life and global functioning by total SVI (coefficients and standard errors).

Model	PART-O Rasch		SWLS		GOS-E	
	Within	Between	Within	Between	Within	Between
Model 1: SVI Total and follow-up year only	−0.078	−1.141***	0.141	−1.112***	−0.001	−0.245***
	(0.106)	(0.075)	(0.120)	(0.088)	(0.021)	(0.017)
Model 2: Adjusted for time-invariant predictors	−0.078	−0.817***	0.141	−0.574***	−0.001	−0.100***
	(0.106)	(0.077)	(0.120)	(0.097)	(0.021)	(0.017)
Model 3: Further adjusted for time-varying predictors	−0.106	−0.271***	0.160	−0.155	−0.004	−0.028*
	(0.103)	(0.067)	(0.119)	(0.094)	(0.019)	(0.012)
Model 4: Further adjusted for tract movement	−0.101	−0.272***	0.157	−0.157	−0.003	−0.028*
	(0.103)	(0.067)	(0.119)	(0.094)	(0.019)	(0.012)

*p < 0.05.
**p < 0.01.
***p < 0.001.
SVI = Social Vulnerability Index, SWLS = Satisfaction With Life Scale, GOS-E = Glasgow Outcome Scale–Extended, PART = Participation Assessment with Recombined Tools.
Model 2 adds respondent sex, age, race, risk of substance use, cause of injury, time to following commands in days, FIM Motor score at admission, FIM Motor score at discharge, residence at discharge, and primary rehabilitation payor.
Model 3 adds marital status, living situation at time of interview, educational attainment, employment, primary mode of transportation, rurality, FIM Motor score at follow-up, and FIM Cognition score at follow-up.
Model 4 adds a binary measure of if respondents moved to a different tract since the previous observation.

PART-O score was 2.89 units higher than observations when the respondent was not employed ($p < 0.001$). Employment status also had a significant between-person effect. Those who were employed across all observations had, on average, 4.09 higher PART-O scores than those who were unemployed at all observations ($p < 0.001$). Within and between effects were also present for the effect of transportation. Relative to times when they reported driving themselves as their primary form of transportation, respondents' community participation scores were 1.54, 0.93, and 1.88 units lower than when they reported riding with someone else, using public transit, or commuting through a special van or bus, respectively ($p < 0.001$). Comparing between individuals, those who rode with someone else had community participation scores an average of 1.78 units lower than other individuals who drove themselves ($p < 0.001$). Individuals who relied on public transit had community participation scores an average 0.84 units lower than individuals who drove themselves ($p < 0.001$). Finally, individuals who traveled via special bus or van scored an average 2.48 units lower on community participation than individuals who drove themselves ($p < 0.001$).

3.3. Models using SVI subtheme scores

Table 4 includes the final model (Model 4) from Table 2, with the results for the SVI Total score shown for reference. Fig. 3 displays coefficient plots across the overall and component SVI scores. We note that we do not describe the individual-level SDoH here, as their effects are the same regardless of the SVI-specific measure included. When considering community participation, the same trend of decreasing magnitudes across models in the between-person comparison was found for Total Scores, Socioeconomic Status, and Household Composition. Between individuals, a one unit increase in Total SVI was associated with a 0.27 unit decrease in the community participation score. Also, when comparing between individuals, a one unit increase in SVI Socioeconomic Status score predicted a 0.32 unit decrease in PART-O score. SVI Household Composition was associated with a 0.23 unit decrease in PART-O for every one unit increase in SVI Household Composition. None of the within comparisons were significant. For life satisfaction, the between effect of Socioeconomic Status was the only component that was significant. When comparing between individuals, for every one unit increase in SVI Socioeconomic Status score, there was a corresponding 0.31 unit decrease in life satisfaction. Finally in Model 4 for global outcome, Socioeconomic Status and Housing Type were significant. When comparing between individuals, a one unit increase in SVI Socioeconomic Status score predicted a 0.03 unit decrease in global outcome. Also, when comparing between individuals, a one unit increase in SVI Housing Type score was associated with a 0.03 unit decrease in global outcome.

4. Discussion

We examined the effect of both neighborhood and individual-level SDoH on TBI-related outcomes. Neighborhood SDoH accounted for differences in TBI outcomes between individuals; however, changes in one's neighborhood over time did not account for changes in outcomes. This result is likely due to the dynamic nature of these outcomes over time, while neighborhood characteristics are more stable, or at least change less quickly, and may require more prolonged exposure to impart effects. Differences in neighborhood SDoH were consistently and robustly associated with differences in community participation, even after accounting for the effects of other factors, both stable and that changed over time. Future research, such as in-depth interviewing, is needed to investigate the underlying mechanisms that account for these relationships.

For global functioning, slightly less robust but still significant effects were found when time varying effects were modeled. While the association for life satisfaction was significant with time invariant factors in the model, it lost significance when time varying effects were added. Researchers have generally found that life satisfaction tends to be stable over time, except when major life events occur and, even then, the effects are often transient (Cummins, 2015; Luhmann et al., 2012; Wettstein et al., 2023). Change in marital status, one of the time varying variables used in our models, is a life event consistently found to impact life satisfaction (Anusic et al., 2014; Sander et al., 2009), which may explain why neighborhood level factors no longer predicted life satisfaction when change in marital status was modeled. The observed differential effects of neighborhood disadvantage on community participation versus life satisfaction is consistent with previous findings (Corrigan et al., 2012; Corrigan et al., 2021), suggesting that a direct effects of one's neighborhood is the ability to participate in activities. The less robust impact on global function may be a function of the purpose of the GOS-E, which was developed to measure neurological recovery associated solely with the TBI, excluding other factors that might impact outcomes (Wilson et al., 2021).

The effect of SVI subthemes, again, were only evident between individuals, not for a given individual over time. Socio-economic Status

Table 3
Mixed effects results for individual-level social determinants of health.

	PART-O Rasch		SWLS		GOS-E	
Sex						
Male (vs Female)	−0.142		−0.433*		−0.053*	
	(0.123)		(0.172)		(0.023)	
Race (White Reference)						
Black	0.356*		−0.606*		0.009	
	(0.175)		(0.240)		(0.031)	
Asian/Pacific Islander	−1.321***		1.171*		0.136*	
	(0.352)		(0.483)		(0.062)	
Hispanic	0.086		1.189***		−0.029	
	(0.203)		(0.277)		(0.035)	
Other	0.113		−0.473		0.112	
	(0.419)		(0.585)		(0.076)	
Primary Insurance (Medicare Reference)						
Medicaid	−0.705**		−2.154***		−0.505***	
	(0.252)		(0.335)		(0.043)	
Private	0.085		−1.779***		−0.395***	
	(0.224)		(0.298)		(0.038)	
Other	−0.421		−2.477***		−0.523***	
	(0.241)		(0.321)		(0.041)	
	Between	Within	Between	Within	Between	Within
Education (HS or Less Reference)						
Some College	1.057***	0.249	0.252	−0.488	0.061*	0.164**
	(0.135)	(0.325)	(0.187)	(0.365)	(0.025)	(0.061)
Bachelors or Higher	1.927***	−0.914	0.582**	−0.241	0.097***	0.159
	(0.157)	(0.481)	(0.218)	(0.565)	(0.029)	(0.095)
Employment Status (Unemployed Reference)						
Employed	4.094***	2.892***	2.749***	1.004***	0.824***	0.420***
	(0.149)	(0.165)	(0.212)	(0.191)	(0.029)	(0.032)
Transportation Mode (Drives Own Vehicle Reference)						
Rides with Someone Else	−1.778***	−1.543***	−1.040***	−1.310***	−0.867***	−0.445***
	(0.164)	(0.197)	(0.227)	(0.216)	(0.030)	(0.035)
Public Transit	−0.836***	−0.925**	−1.106***	−0.684*	−0.208***	−0.064
	(0.233)	(0.296)	(0.321)	(0.324)	(0.044)	(0.054)
Special Bus/Van	−2.481***	−1.875**	−1.086	−1.325*	−0.781***	−0.363***
	(0.484)	(0.611)	(0.612)	(0.570)	(0.073)	(0.083)
Urbanicity (Rural Reference)						
Urban	0.264	0.097	−0.139	−0.191	0.022	0.039
	(0.154)	(0.329)	(0.214)	(0.381)	(0.028)	(0.063)
Suburban	0.261	−0.031	−0.258	−0.109	−0.004	0.055
	(0.151)	(0.293)	(0.211)	(0.343)	(0.028)	(0.056)

*p < 0.05.
**p < 0.01.
***p < 0.001.
SWLS = Satisfaction With Life Scale, GOS-E = Glasgow Outcome Scale–Extended, PART = Participation Assessment with Recombined Tools, SVI = Social Vulnerability Index. Numbers in parentheses are standard errors.

was consistently associated with each outcome, with a substantial relationship evident for both community participation and life satisfaction and a modest association with global functioning. The importance of neighborhood socio-economic status on health outcomes aligns with research for multiple other acute and chronic conditions (Social Determinants of Health; Healthy People 2030 | Health.Gov, 2024). Higher socio-economic status areas likely are higher in economic resources and opportunities that facilitate participation, satisfaction, and functioning. We also observed unique subtheme associations with specific outcomes. Household Composition was highly associated with community participation; areas with more older and young people, those with disability, and who are not proficient in English could hamper participation among those with TBI in those areas. Housing Type and Transportation was modestly associated with global functioning, possibly reflecting how particular living situations with shared quarters and lack of transportation can prevent opportunities and access to address functioning.

Perhaps more surprising than the observed significant associations was the non-significant relationship between the Racial/Ethnic Minority Status subtheme and outcomes, especially given the robust findings from previous individual-level studies of TBI. Racial/ethnic composition within a neighborhood may not equate to disadvantage, such as socioeconomic disadvantage (Ayscue et al., 2017), experienced by individuals from minoritized racial and ethnic groups. That is to say, individual-level race/ethnicity may serve as a more direct proxy (Lett et al., 2022) for broader systemic and attitudinal barriers encountered by an individual regardless of the neighborhood they live in. The effects of neighborhood composition may be capturing different SDoH, and it is likely there is an interaction between these individual-level and neighborhood-level factors.

Though the observed effect of neighborhood disadvantage on community participation was significant, individual-level SDoH also showed substantial associations on all three outcomes. At the individual level, both being employed and driving one's own vehicle had substantial effects across all three outcomes. Notably, these effects were present both within (i.e., a change from one time point to another in employment and/or driving) and between individuals (differences in subgroups who were employed or driving themselves were associated with community participation). Though it is possible that both employability and the ability to drive are proxies for having less severe deficits from TBI, our models included indicators of initial injury severity (time to follow commands), early functional recovery (motor function at rehabilitation admission and discharge), and both motor and cognitive function at later follow-ups. Prior studies of these outcomes have found similar

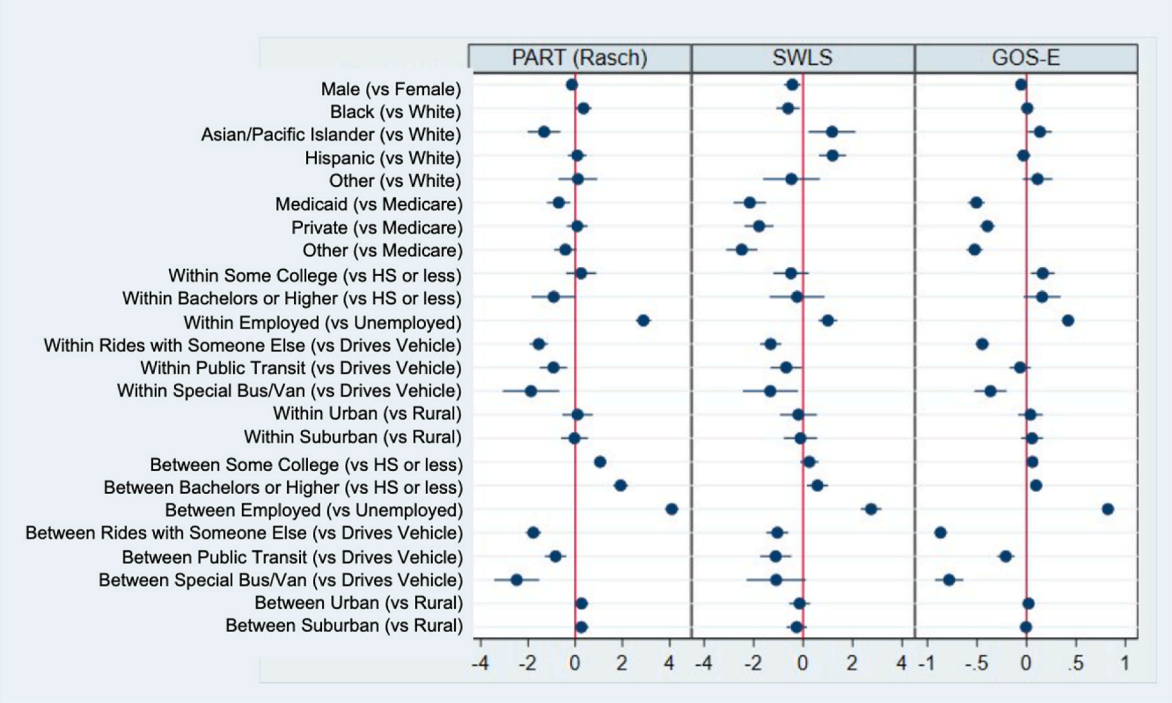

Fig. 2. Coefficient Plot of Individual Level Social Determinants of Health (PART = Participation Assessment with Recombined Tools, SWLS = Satisfaction With Life Scale, GOS-E = Glasgow Outcome Scale–Extended, HS = high school).

Table 4
Mixed effects results for overall and subthemes of SVI scores.

	PART-O (Rasch)		SWLS		GOS-E	
	Within	Between	Within	Between	Within	Between
Standardized SVI Total Themes	−0.101	−0.272***	0.157	−0.157	−0.003	−0.028*
	(0.103)	(0.067)	(0.094)	(0.094)	(0.019)	(0.012)
Standardized SVI Socioeconomic Status	−0.083	−0.322***	0.073	−0.314***	0.004	−0.029*
	(0.103)	(0.067)	(0.120)	(0.093)	(0.019)	(0.012)
Standardized SVI Household Composition	−0.077	−0.228***	0.085	−0.172	0.005	−0.019
	(0.084)	(0.065)	(0.097)	(0.090)	(0.016)	(0.012)
Standardized SVI Housing Type	−0.035	−0.102	0.099	0.059	−0.009	−0.030*
	(0.087)	(0.063)	(0.101)	(0.088)	(0.016)	(0.012)
Standardized SVI Minority Status	−0.104	−0.095	0.223	0.069	−0.025	0.015
	(0.119)	(0.077)	(0.137)	(0.107)	(0.022)	(0.014)

SWLS = Satisfaction With Life Scale, GOS-E = Glasgow Outcome Scale–Extended, PART = Participation Assessment with Recombined Tools, SVI = Social Vulnerability Index.

relationships, with the ability to drive a consistent factor (Erler et al., 2018; Juengst et al., 2022; Rapport et al., 2008; Sanders et al., 2023). The inability to drive oneself could limit a person's ability to leave their home, thus reducing community participation (the majority of items that contribute to the PART-O Rasch total require leaving one's home (Malec et al., 2016) and consequently reducing life satisfaction. A recent study found that psychosocial barriers – rather than physical capability – were the most cited barriers to driving after TBI (Sanders et al., 2023). The ability to drive may be capturing the effect of other potential neighborhood-level factors not measured by the SVI (e.g., access to public transportation). The nature of these barriers may be fruitful topics for further investigation of modifiable factors.

Unsurprisingly, being employed was associated with change over time in all outcomes, which is consistent with previous research strongly supporting this association (Dams-O'Connor et al., 2023; DiSanto et al., 2019). Results demonstrating within-person effects of employment—that is, change over time in employment status resulted in a change in outcomes—highlight the importance of supports for returning to work and maintaining stable employment. Previous studies have found that independence in transportation is strongly associated with employment stability (DiSanto et al., 2019). Though the primary indicator for independence in transportation was driving oneself, it is important to note that the availability of public transportation and not just the ability to use it are potentially important neighborhood-level factors that the SVI does not capture. All considered, the strength of the within-person effects for employment and independence in driving may suggest that these abilities could be high-value targets for actionable interventions.

Having Medicare as one's primary insurance during inpatient rehabilitation was highly associated with better life satisfaction and global functioning. This relationship could be due to age, though age was a covariate in modeling. It is more likely that Medicare eligibility was an indirect indicator of another age-related factor. For instance, falls are the most common etiology of TBI in older adults, while motor vehicle crashes and violent encounters are more likely among younger adults. Etiology conveys different methods by which the brain is damaged,

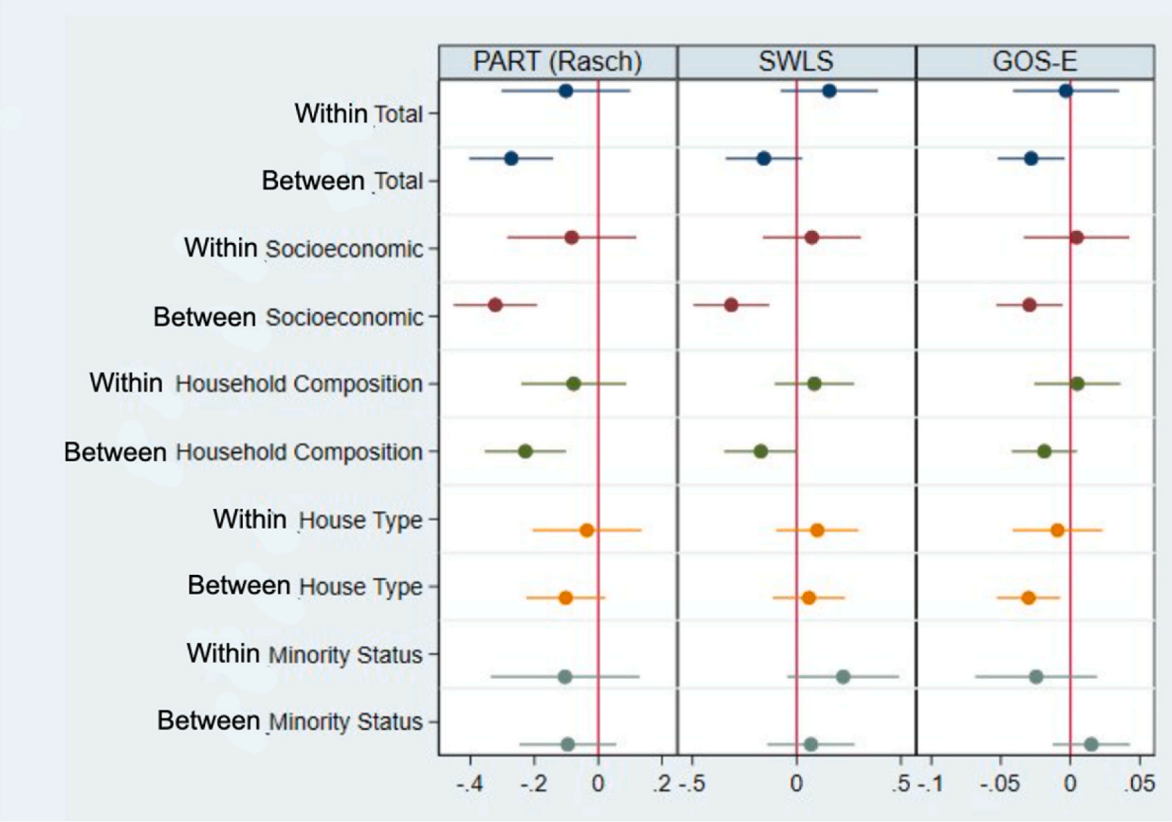

Fig. 3. Coefficient plot of overall and subtheme SVI scores (part = participation assessment with recombined tools, SWLS = satisfaction with life scale, GOS-e = glasgow outcome scale–extended).

which may in turn result in deficits that allow (Juengst et al., 2022) better global functioning. Similarly, research in both TBI and the general population (Baird et al., 2010) consistently finds that older adults report better life satisfaction than younger adults, a finding likely associated with other age-related social factors.

Respondents with higher than a high school education had better community participation, but not life satisfaction or global functioning. This beneficial effect could be an indicator of a differential impact of cognitive reserve. At the same time, another viable explanation for this result comes from the Theory of Fundamental Causes (Link & Phelan, 1995). In making an argument for the robust relationships among socioeconomic status, inclusion and health disparities, the Theory of Fundamental Causes assumes that the social benefits related to having more education may provide opportunities for better recovery. Participants with more education may belong to social networks or have grouped resources that promote higher levels of success while recovering from injury. At the same time, it is likely that those who have completed more education have networks that can provide more opportunities for success and/or may have higher understandings of the recovery process, simplifying the community inclusion experience.

Also of interest in our findings were insignificant relationships. Perhaps most notably, individual-level indicators of sex, race/ethnicity, and rurality had little or no association with outcomes. As reviewed earlier, each of these individual differences have previously been found to be associated with TBI outcomes (Arango-Lasprilla et al., 2008, 2009, 2011; Arango-Lasprilla, Rosenthal, Deluca, Cifu, et al., 2007; Arango--Lasprilla, Rosenthal, Deluca, Komaroff, et al., 2007; Kuerban and Dams-O'Connor, 2022). As noted earlier, individual-level race/ethnicity is a proxy (Lett et al., 2022) for the effects of systematic racism. Inclusion of neighborhood-level factors, such as socioeconomic status, in our models may capture some of these systemic factors directly, negating the statistically significant effects of individual-level race/ethnicity. Related to sex/gender effects, past findings are mixed and limited by a lack of differentiation between the effects of sex, gender, and their intersection. A summary of the chronic effects on outcomes after TBI based on TBIMS studies noted only sporadic effects of sex (Dams-O'Connor et al., 2023) (which, again, was likely conflated with gender effects). Like race/-ethnicity, gender is a social construct that serves as a proxy for the experience of barriers and facilitators to outcomes. More in-depth investigation is needed about how sources of marginalization are experienced and captured for study.

Several limitations exist inherent to our design and available data. The TBIMS NDB includes data from healthcare centers across the US; however, participants are not enrolled using a complex survey sampling strategy designed to be representative. Applied to the present study, this means the SVI values cannot be considered a random representation of the population. Despite this, research has shown that the TBIMS sample is largely representative of the US population receiving inpatient rehabilitation for a primary diagnosis of TBI (Corrigan et al., 2012; Cuthbert et al., 2012). However, persons who receive inpatient rehabilitation have experienced more severe TBIs which result in worse long-term outcomes. Thus, the sample studied does not reflect the full range of TBI severity. Another limitation resulted from the available data limiting our ability to comprehensively study individual-level SDoH. The TBIMS does not include key variables, such as food and housing security, that are known SDoH (Marmot & Wilkinson, 2005); however, variables such as these would be candidates for targeted, modular TBIMS studies. Strengths of our study included simultaneous evaluation of individual and neighborhood SDoH, which ameliorates some concerns over ecological fallacy bias. We also had a large sample with longitudinal follow-up over many years post-injury, which afforded us the ability to evaluate between- and within-person effects of SDoH variables.

5. Conclusions

Neighborhood level SDoH accounted for differences in outcomes between individuals who have had a TBI but change in a given individual's neighborhood did not. At the individual level, the ability to work and drive one's own car were highly associated with positive outcomes. These findings may reflect that long-term recovery from TBI is more dynamic than the evolution of change in neighborhoods. SDoH, including neighborhood-level indicators, were more robustly associated with community participation than global functioning or life satisfaction. Among neighborhood-level indicators, socio-economic status showed robust and consistent between-person relationships. Sex, rurality, and minoritized status at the individual-level had no or minimal relationships with outcomes; and minoritized status at the neighborhood level was similarly poorly associated with outcomes. Results of this study could facilitate identification of persons at greater risk for suboptimal outcomes and may provide some insight for development of proactive, community interventions.

The Socioeconomic Status subtheme score is calculated as the sum of the percentiles at which the civilians/households are ranked for the criteria of income below the poverty line, unemployment, per capita income estimate, and no high school diploma. The Household Composition subtheme is comprised of the percentiles for the proportion of persons over the age of 65, under the age of 17, and single parent households with children under 18. In 2020, this category also included these calculations for civilians with disabilities and English language proficiency. The Minority Status subtheme calculation changed from 2010 to 2020. In 2010 it was calculated as the sum of the percentiles of the proportion of the population who were not White, non-Hispanic and the proportion of persons who reported speaking English "less than well" over the age of 5. In 2020, Minority Status was calculated as the percentile of the proportion of those other than non-Hispanic, Whites. Language proficiency was moved to Household Composition, now called Household Characteristics. The Housing Type subtheme was calculated in the same way as the other subthemes and included the proportions living in housing structures with 10 or more units, living in mobile homes, living with more people than rooms, having no vehicle access, and living in institutionalized group quarters.

CRediT authorship contribution statement

John D. Corrigan: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Mike Vuolo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Rebecca Shankman:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology. **Jennifer Bogner:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Cynthia L. Beaulieu:** Writing – review & editing, Writing – original draft, Validation, Methodology, Data curation, Conceptualization. **Amanda L. Botticello:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Kathryn A. Hyzak:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Shannon Juengst:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization. **Raj G. Kumar:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Conceptualization. **Cecilia Mengo:** Writing – review & editing, Writing – original draft, Validation, Methodology, Conceptualization.

Ethics statement

The above-named manuscript has not been published previously.

The article is not under consideration for publication elsewhere.

The article's publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out.

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Declaration of competing interest

None of the authors have financial or personal relationships with other people or organizations that could inappropriately influence or bias this work and thus have nothing to declare.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ssmph.2025.101795.

Data availability

Data will be made available on request.

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