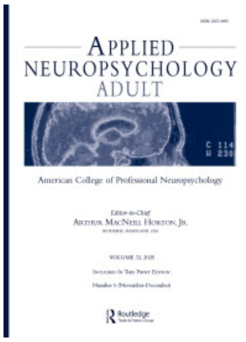

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Factor analysis of neuropsychological attention measures with mild traumatic brain injury patients

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ABSTRACT

This study explored the factor structure of commonly used neuropsychological tests to assess attention in individuals with mild traumatic brain injury (mTBI). Archival data were drawn from 269 patients (63% women; M_age = 47.8, SD = 14.6) seen at a private outpatient clinic between 2018 and 2023. Participants self-identified primarily as White (84%), with additional representation from Asian (10%), Hispanic/Latinx (3%), Black (1%), Middle Eastern/North African (1%), and Multiracial (1%) backgrounds. Exploratory factor analysis (EFA) with oblimin rotation was used to examine performance on the NAB Numbers & Letters Test, Paced Auditory Serial Addition Task (PASAT), Trail Making Test A & B, Digit Span, Arithmetic, and Coding. The EFA supported a four-factor solution that accounted for 58% of the total variance. These factors reflected: (1) visual attention and psychomotor speed, (2) auditory attention and working memory, (3) visuospatial scanning and search, and (4) interference management. The findings highlight the multifactorial structure of attention in mTBI and support the clinical relevance of using diverse measures to assess distinct attentional processes.

KEYWORDS
attention; cognitive functioning; factor analysis; mild traumatic brain injury; neuropsychological assessment

Introduction

In 2020, there were approximately 223,135 traumatic brain injury (TBI) hospitalizations and 64,362 TBI-related deaths in the United States (CDC, 2024). Most TBIs that occur each year are considered mild TBIs (mTBI), also known as concussive brain injuries or concussions. While mTBIs are typically not life-threatening, they can still pose considerable health consequences and risk to those sustaining them. TBI is defined as "an alteration in brain function, or other evidence of brain pathology, caused by an external force" (Menon et al., 2010, p. 1637). New diagnostic criteria for mild traumatic brain injury (mTBI), also referred to as a concussion, was developed by the American Congress of Rehabilitation Medicine (ACRM) in 2023. The criteria focus on ensuring accuracy and consistency in diagnosing mTBI across various contexts, including civilian trauma, sports, and military settings. The diagnostic criteria for mTBI emphasize the following key components: Diagnosis requires a biomechanically plausible mechanism of injury, where an external force results in a disruption of brain function, The injury must produce at least one acute clinical sign of brain dysfunction. These signs include loss of consciousness, alteration of mental status (e.g., disorientation, confusion, or slowed responses, post-traumatic amnesia for events following the injury, or other observable neurological signs, such as motor incoordination or seizures. The injured individual must experience at least two new or worsened acute symptoms following the injury. These symptoms can include cognitive symptoms, physical symptoms, or emotional symptoms. The onset of symptoms should occur within 72 hours of the injury. Objective evidence of brain dysfunction can include cognitive impairment, balance problems, or oculomotor dysfunction identified through clinical examination. Elevated blood biomarkers indicative of brain injury are also supportive of mTBI but are not necessary for diagnosis. Neuroimaging is not required to diagnose mTBI. However, if imaging (such as CT or MRI) reveals trauma-related abnormalities, this would confirm a TBI diagnosis. The ACRM criteria recognize "mild TBI with neuroimaging evidence of structural intracranial injury" when imaging shows abnormalities. Additionally, the diagnosis of mTBI requires that the clinical signs and symptoms are not better explained by other factors, such as intoxication, psychological trauma, or other health conditions (American Congress of Rehabilitation Medicine (ACRM), 2023)

Attentional sequelae after mTBI

While not all mTBIs result in cognitive sequelae, research has documented the damaging effect that concussive brain injury can have on attention in some patients (Pontifex et al., 2012). The literature surrounding mTBIs has been controversial, with a history of viewing any cognitive deficits associated with concussive brain injuries as temporary (Iverson et al., 2008; Nelson et al., 2019). However, growing research has suggested that there may be longer-lasting effects for a small population of those who sustain mTBI

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(Cancelliere et al., 2023; Cooksley et al., 2018). A challenge in the current literature is determining exactly how many individuals might have persisting symptoms. Studies suggest that 15-30% of patients have cognitive impairments (e.g., deficits in memory, attention, processing speed, executive functioning, visuo-perceptual functioning) from mTBI after one year (Carroll et al., 2020; McInnes et al., 2017; Rabinowitz & Levin, 2014) and a recent argument by McInnes et al. (2017) suggests that up to 55% of those who have sustained mTBI experience long-term symptoms.

Due to the types of accidents that tend to lead to mTBI (e.g., car crashes, sports injuries), traumatic axonal injury (TAI) is a common form of brain damage that can occur (Bruggeman et al., 2021). TAI results from shearing forces that cause damage to axons in the brain, which transmit electrical impulses to other neurons, when the head is subjected to sudden acceleration or deceleration (e.g., with mTBI); this causes the brain to move rapidly within the skull (Bruggeman et al., 2021; Graham et al., 1987). The damage to the axons can disrupt the communication between different areas of the brain and result in a range of neurological symptoms, including impairment in attention (Shenton et al., 2012). The problem with TAI is that it is often difficult to diagnose as it may not be visible on routine imaging tests such as computerized tomography (CT) scans or magnetic resonance imaging (MRI). One of the common lasting symptoms of mTBI is attentional deficit, specifically in the areas of attention span (i.e., the amount of time one can focus on a task without becoming distracted), divided attention (i.e., the ability to process and respond to multiple tasks or demands simultaneously), shifting attention (the cognitive ability to change focus between different tasks or aspects of the environment, also known as attention switching or task switching), and information processing speed (the rate at which one can take in, understand, and respond to information; Wu et al., 2020). Because of the importance of attention in our daily lives and the difficulty of assessing TAI after mTBI, improving measurement of attentional declines in individuals after a concussive brain injury is important for the well-being of individuals who have sustained such an injury (Paré et al., 2009).

Theories of attention

Neuropsychological assessments commonly use standardized batteries to evaluate cognitive abilities, but questions of construct validity and sensitivity remain. Many tests tap multiple cognitive domains simultaneously, complicating interpretation (Kessels, 2019; Sohlberg & Mateer, 1989). Factor analysis has been used to uncover the latent structures underlying such tests, aiding in efforts to clarify what cognitive constructs are being measured (Jones et al., 2015; Price et al., 2002). Mirsky et al. (1991) proposed a multidimensional model of attention that included focusing, sustaining, shifting, and encoding components, supported by principal components analysis. Subsequent work by Schmidt et al. (1994), however, yielded inconsistent factor structures and questioned whether statistical distinctions between tests necessarily reflect meaningful cognitive constructs. More recently, Treviño et al. (2021) found that common neuropsychological tests diverged from experimental attention paradigms, reinforcing the view that measures like Digit Span and Arithmetic reflect complex constructs, such as working memory, rather than pure attention.

Despite these complexities, research continues to suggest that attention is a multifaceted process comprising separable but interrelated components. While some studies, such as Huang et al. (2012), have proposed a unitary "general attention factor," most analyses have identified multiple factors, including distinct elements of sustained, transient, and spatiotemporal attention (Skogsberg et al., 2015). There remains minimal overlap across studies in terms of the specific tests employed, highlighting the need for further research to evaluate the validity of commonly used clinical measures. Drawing on Mirsky's (1987) conceptualization of attention as consisting of separable processes, the current study hypothesizes a multifactorial structure that may also capture related constructs like working memory and processing speed. Although closely related, attention and working memory are increasingly understood as distinct systems, attention functioning primarily as a mechanism of prioritization and selection, while working memory governs the temporary storage and manipulation of task-relevant information (Oberauer, 2019).

Study aim

In summary, the limited availability of psychometrically and theoretically sound neuropsychological measures of attention, along with lack of sensitivity to deficits among mTBI patients requires deeper examination of factors of attention measured by these tests. Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) are both common approaches for this type of analysis. As there is a scarcity of studies available which use overlapping measures of attention, EFA was chosen as the approach in this study. As such, the aim of this study is to identify the underlying factor structure of a battery of commonly used attention measures in mTBI patients, including the NAB N&L Test, PASAT 2" and 3", Trail Making Tests A and B, and WAIS Digit Span, Coding, and Arithmetic.

Research question and hypotheses

This study seeks to answer the research question of the factor structure of a battery of measures used to assess attention among mTBI patients. Included in this analysis are two less common, but perhaps more sensitive measures (NAB N&L Test, PASAT) and more commonly used, but perhaps less sensitive measures (DS, Arithmetic, Coding, and TMT). Drawing from foundational research in the field, I hypothesized that a five-factor solution would fit the data best and map onto the areas of *selective attention, sustained attention, divided attention, processing speed,* and *working memory*. Specifically, I hypothesized that the Arithmetic and Digit Span tests would load onto the "working memory" factor, a conjecture informed by the work of Mirsky and Treviño, who documented these tests' reliance on working memory capacities. Similarly, based on consistent findings across studies by Mirsky, Schmidt, and Treviño, I hypothesized that the Trail Making Test (TMT) and the Coding test would load onto the "Selective Attention" and "Processing Speed" factors, reflecting their shared demands on these cognitive processes.

Furthermore, I hypothesized that the NAB Numbers and Letters Test would demonstrate a multifactorial load, specifically with Part D loading onto "Divided Attention," Part A loading onto sustained "Sustained Attention" and "Processing Speed," and Part B and C loading onto the "Selective Attention" factors (White & Stern, 2003). This expectation aligns with the test's design to assess these varied aspects of attention. Additionally, I anticipated that the PASAT would cross-load onto the "Divided Attention" and "Working Memory" factors, based on Crawford et al. (1998) and Cicerone's (1997) research which highlights the test's utilization of working memory and processing speed alongside its measure of divided attention. These hypotheses aim to refine our understanding of how specific neuropsychological tests map onto distinct cognitive domains in mTBI patients.

Method

Participants

The present study drew from archival data of patients presenting in 2018–2023 to a private outpatient clinic in the Pacific Northwest. Participants were 269 individuals between the ages of 18–81 ($M = 47.8$, $SD = 14.6$). Participants self-identified their ethnicity as 84% White, 10% Asian, 3% Hispanic/Latinx, 1% Black, 1% Middle Eastern/North African, and 1% Multiracial. Gender of participants was self-identified as 63% women and 37% men. Inclusion criteria were patients presenting for evaluation in the context of a mild traumatic brain injury as defined by the American Congress of Rehabilitation Medicine, a disruption of brain function characterized by at least one of the following: a) a brief loss of consciousness, b) memory loss for events immediately before or after the incident, c) a change in mental state during the accident (such as feeling dazed, disoriented, or confused), or d) focal neurological deficits that may be temporary. Patients were either diagnosed with mTBI by their referring provider or the neuropsychologist at this clinic based on information gleaned from the clinical interview according to ACRM guidelines. Due to variability in available clinical records, no other inclusion or exclusion criteria were utilized. Due to the archival nature of the dataset, objective injury severity indicators such as Glasgow Coma Scale scores, neuroimaging results, and duration of loss of consciousness were not uniformly available and could not be included in the analysis. However, all participants met ACRM diagnostic criteria for mTBI, and diagnostic determinations were confirmed by licensed neuropsychologists using structured clinical interviews and available documentation.

Measures

This study includes several neuropsychological measures commonly used to assess attention in individuals with mild traumatic brain injury (mTBI), drawing from prior factor analytic research. The NAB Numbers & Letters Test (Stern & White, 2003) and the Paced Auditory Serial Addition Task (PASAT; Tombaugh, 2006) are less commonly used but have demonstrated sensitivity to attention deficits following TBI. Digit Span (DS), despite its widespread use, has shown weak predictive validity for everyday attention and may better reflect working memory than pure attentional capacity (Groth-Marnat & Baker, 2003; Treviño et al., 2021). Arithmetic and Coding, subtests from the WAIS (Pearson, 2009), are also included due to their appearance in prior attention factor analyses, although Arithmetic is typically associated with working memory. Trail Making Test A and B, frequently used in clinical evaluations, assess visual scanning, processing speed, and set-shifting abilities and were consistently included in previous models of attentional structure (Mirsky et al., 1991; Schmidt et al., 1994; Treviño et al., 2021).

The selection of measures for the present factor analysis was guided by both theoretical considerations and clinical utility. Although prior studies examining the structure of attention have employed varying combinations of tests, often yielding differing factor solutions, this study aimed to incorporate a clinically representative and theoretically grounded battery. Specifically, the test selection included both widely established measures and less frequently studied, yet promising, tools such as the NAB Numbers & Letters Test and the PASAT. These instruments are routinely used in neuropsychological evaluations of individuals with mild traumatic brain injury (mTBI). The combination of tests used in this study extends previous research conducted by Mirsky, Schmidt, and Treviño, who each employed overlapping but non-identical sets of attention measures. By including a blend of traditional and newer tools in a relatively large clinical sample, this study enhances ecological validity and contributes novel insight into the factor structure of attention in mTBI, offering findings that are both theoretically informative and directly applicable to real-world clinical practice.

NAB number & letters test (N&L test; Stern & White, 2003)

Part A measures psychomotor speed, efficiency, and errors, produced from the timed task of the participant marking all the "X's" on a page of numbers and letters. Parts B and C measure efficiency of selective attention tasks, in which participants are asked to count the number of "X's" in each row and add the numbers in each row, respectively. Part D measures efficiency of a more complex attention task, in which participants are asked to simultaneously mark the "X's" in each row and add the numbers. Part D also measures the disruption of a visual divided attention task, comparing speed to the first part of Part A, which allows assessors to interpret if dividing one's attention significantly reduces attentional abilities. The NAB Numbers & Letters Test demonstrates good internal consistency, with split-half reliability coefficients of .84 and .89 for Forms 1 and 2, respectively (Stern & White, 2003). Zgaljardic and Temple (2010b) conducted preliminary studies to examine the validity of the NAB N&L test as a measure of attention among TBI patients and reported that the NAB N&L test is sensitive to the cognitive impairments typically observed in TBI patients. Donders and Levitt (2012) found that the Numbers and Letters subtest showed statistically significant sensitivity to brain injuries, evidenced by the lower performance scores of TBI patients compared to controls ($F(3,104)=14.16$, $p < .0001$).

Paced auditory serial addition task (PASAT; Gronwall & Sampson, 1974)

Participants are auditorily presented with a series of random numbers ranging from 1 to 9. They are instructed to sequentially add pairs of numbers, where each number is added to the number that immediately precedes it. For instance, if the sequence starts with "1" followed by "9," the participant's response should be "10." If the next number in the sequence is "4," the participant should respond with "13" by adding "4" to the previous number "9," rather than adding it to their own response of "10." This response pattern continues throughout 60 items until the end of the trial and is done in two rounds, the first with numbers presenting at a rate of one every three seconds, the second round with numbers presenting at a rate of one every two seconds. The numbers are played on a recording to ensure standardization. Multiple studies have shown the PASAT to demonstrate strong internal consistency with correlations between scores on individual trials typically falling within the range of .76 to .95 among both mTBI samples and other groups (Macleod & Prior 1996; Ponsford & Kinsella, 1992; Sherman et al., 1997).

WAIS digit Span (DS; Pearson, 2009)

In Digit Span Forward (DSF), participants must repeat a sequence of digits, with the number increasing gradually across trials. The digits are presented orally at a rate of 2 per second to prevent rehearsal. The sequence length starts with 2 digits and progresses up to 10 digits. Digit Span Backward (DSB) assesses the ability to recall the digits in reverse order (e.g., recalling 3-2-1 instead of 1-2-3), and Digit Span Sequencing (DSS) assesses the ability to recall digits from lowest to highest. According to the WAIS-IV technical manual, the Digit Span subscale scores exhibit a mean internal consistency of .93, indicating a high level of internal consistency reliability (Pearson, 2009).

WAIS coding (CD; Pearson, 2009)

Coding involves a set of nine numbers, each linked with a unique abstract symbol, and a response sheet comprising numbered boxes with an upper part containing a number and a lower part left blank. Participants are tasked with quickly replicating the accurate designs beneath their corresponding numbers within a time constraint of 120 seconds. It yields a raw score based on total correct responses, which are then transformed into scaled scores with an average of 10 and a standard deviation of 3. The WAIS Coding subtest in the Wechsler Adult Intelligence Scale – Fourth Edition (WAIS-IV) replaced the Digit Symbol – Coding (DS-C) subtest of the Wechsler Adult Intelligence Scale – Third Edition (WAIS-III). A validity investigation documented in the WAIS-IV: Technical and interpretive manual reported that when both the WAIS-IV and WAIS-III were administered to the same subjects, DS-C and CD subtest scores exhibited strong correlations, irrespective of whether the participants were healthy controls ($n = 240$; $r = .85$), individuals with borderline intelligence ($n = 24$; $r = .62$), or those with mild intellectual disability ($n = 25$; $r = .87$).

WAIS arithmetic (Pearson, 2009)

Participants are required to solve a series of arithmetic word problems presented auditorily of increasing difficulty. The test is designed to measure various aspects of intelligence and cognitive processing, specifically, working memory (Weschler, 2008). However, research has found Arithmetic to be a weak indicator of working memory in the past (Gignac & Watkins, 2013). The Arithmetic subtest has demonstrated good internal consistency, with Cronbach's alpha typically reported in the range of .83 to .85, and test-retest reliability .80 (Weschler, 2008).

Trail making test (TMT; Partington & Leiter, 1949)

The Trail Making Test (TMT) Parts A and B are neuropsychological tests frequently used to assess visual attention, task switching, and cognitive processing speed. The TMT shows high reliability, with test-retest reliability coefficients typically reported between 0.7 and 0.9 for both parts of the test. This suggests that the test produces consistent results over repeated administrations under similar conditions. A set of initial Pearson product-moment correlations established a relationship between the direct scores of TMT-A and TMT-B ($r = .73$), reinforcing the assumption that both scores are influenced by shared cognitive factors (Sanchez-Cubillo et al., 2009).

Procedure

Participants included mTBI patients presenting for assessment underwent a structured neuropsychological evaluation. The procedure was designed to be part of routine clinical assessments, thereby ensuring that participants did not undergo any additional tests beyond standard clinical practice. This methodology allowed for the collection of data in a real-world clinical setting, reflecting genuine clinical encounters rather than controlled experimental conditions. As such, informed consent from participants was not required. The study protocol was reviewed and approved by the institution's Institutional Review Board (IRB), and all procedures adhered to ethical standards for the secondary use of clinical data in research.

The battery of neuropsychological tests varied among participants depending on individual clinical needs; however, most patients completed all the measures analyzed in this study. The tests included, but were not limited to, the NAB Numbers and Letters Test, Paced Auditory Serial Addition Test (PASAT), Trail Making Tests, and WAIS Digit Span, Arithmetic, and Coding subtests. The order of test administration was not standardized across participants but varied based on clinical necessity and patient presentation, consistent with typical clinical procedures at the data collection site. This variability is acknowledged as a potential limitation and is addressed in the Discussion section. Assessments were chosen based on their relevance to assessing different aspects of attention and individual patient needs.

The choice to use Exploratory Factor Analysis (EFA) rather than Confirmatory Factor Analysis (CFA) in this research stems from the study's objective to identify the underlying factor structure of neuropsychological tests flexibly without imposing an overly conservative, pre-specified factor model in CFA. Few studies have examined the structure of multiple attention measures, particularly in an mTBI sample, making it more appropriate to utilize EFA, which is particularly useful in situations where the relationships between variables are not well understood. Thus, the choice to use EFA in this study was made based on its exploratory nature due to the lack of research using uniform attention assessments in this area of study. All analyses were be run R using the *"psych"*, *"tidyverse"*, *"MASS"*, *"sjstats"*, and *"apaTables"* packages.

Results

Preliminary analyses

A total of 283 participants were in the initial sample. The missingness of individual variables varied, with most falling within the range of 3% to 9%. Notably, the PASAT variables exhibited a higher degree of missingness, ranging from 33% to 35% due to being administered less frequently. To address missing data, we utilized multiple imputation to estimate missing values (Enders 2022). Multiple Imputation using Markov Chain Monte Carlo (Geyer, 1992; MCMC) was applied with 10 iterations to enhance the accuracy of the imputed data, aligning with recommendations for maximizing precision (Enders 2022; Graham, 2009). Outliers beyond three standard deviations from the mean were then identified and removed using the *z*-score method which led to the removal of 14 cases ($N = 269$). Descriptive statistics were then computed, revealing no anomalies in skew and kurtosis. All tests included in the exploratory factor analysis were analyzed using scaled scores based on un-imputed data, and assumptions for EFA were assessed through examination of skewness and kurtosis values.

Determining an adequate sample size for exploratory factor analysis (EFA) requires a combination of empirical guidelines and informed judgment (Ma et al., 2019). Several standards have been widely adopted in the literature, including a recommended minimum of 100 participants for factor analysis (Costello & Osborne, 2005; Gaskin & Happell, 2014; Kline, 2023). In accordance with the commonly cited guideline suggesting a 10:1 participant-to-variable ratio (Plichta & Kelvin 2012), a minimum of 110 participants would be required for the current analysis involving 11 variables. The final sample size of 269 therefore exceeds these recommendations. Sampling adequacy was further supported by a strong Kaiser-Meyer-Olkin (KMO) value and acceptable inter-item correlations, indicating the data were appropriate for factor extraction. EFA was conducted to identify the underlying latent factors accounting for shared variance among the observed variables.

Following data cleaning procedures, a correlation matrix was calculated. Multicollinearity was assessed among predictor variables to ensure the integrity of the statistical models. Correlation coefficients were computed for all pairs of variables. Notably, the variables NAB A Speed and NAB A Efficiency exhibited a very strong positive correlation of approximately 0.97, suggesting redundancy in the information captured. The decision to exclude NAB A Speed from this analysis was based on the principle of parsimony and to mitigate potential multicollinearity issues in subsequent analyses. This step ensured a more robust and interpretable model by focusing on independent predictors. Additionally, a pronounced positive association was observed between PASAT 3" and PASAT 2", with a correlation coefficient of approximately 0.77. However, Digit Span displayed weaker correlations with other variables, as indicated by coefficients ranging from 0.04 to 0.31. These findings provide initial insights into the relationships among variables in our investigation.

The dimensionality of the attention items was analyzed using principal axis factoring. First, data screening was conducted to determine the suitability of the data for these analyses. The Kaiser-Meyer-Olkin measure of sampling adequacy (KMO; Kaiser, 1960) represents the ratio of the squared correlation between variables to the squared partial correlation between variables. KMO ranges from 0.00 to 1.00 – values closer to 1.00 indicate that the patterns of correlations are relatively compact, and that component analysis should yield distinct and reliable components. In our dataset, the KMO value was .70, indicating acceptable sampling adequacy. The Barlett's Test of Sphericity tests whether the correlations among variables in a data set differs significantly from an identity matrix—meaning constant variance across items but no covariance between them. When the *p* value for the Bartlett's test is $< .05$, we are fairly certain that variables are intercorrelated rather than independent. In our dataset, $\chi^2(78)= 1652.95$, $p <.001$, indicating the correlations between items are sufficiently large enough for principal axis factoring. The determinant of the correlation matrix alerts us to any issues of multicollinearity or singularity and should be larger than 0.00001. The determinant was 0.002, indicating the data was suitable for analysis.

While theory-informed expectations were used to guide interpretation of the findings, no widely accepted or replicable factor structure exists for attention measures in clinical mTBI populations. Therefore, an exploratory approach was selected to identify latent relationships among commonly used neuropsychological tests in real-world clinical practice. Confirmatory factor analysis (CFA) may be appropriate for future research once a more established structural model has been validated across samples and test batteries.

Factor analysis

Four criteria were used to determine the number of factors to rotate: a priori theory, the scree test, the Eigenvalue-greater-than-one criteria, and the interpretability of the solution. Kaiser's eigenvalue-greater-than-one criteria suggested four factors, which collectively explained 60% of the variance in test scores. The scree plot showed an inflexion point that justified retaining four factors. A parallel analysis was then performed as an alternate way to determine the appropriate number of factors to retain (Henson & Roberts, 2006). This suggested that six factors might best fit the data, but the eigenvalues of factors five and six were far below the minimal acceptable eigenvalue of 1 (Kaiser, 1960) so four were retained.

An oblimin rotation procedure was selected for the exploratory factor analysis to allow for the possibility of correlated factors. This choice is supported by theoretical and empirical evidence suggesting that attentional processes are often interrelated rather than orthogonal (Mirsky et al., 1991). Given the likelihood of shared variance among these constructs, an oblique rotation was considered more appropriate than an orthogonal method such as varimax. This methodological decision aligns with contemporary best practices in exploratory factor analysis for cognitive and psychological constructs (Costello & Osborne, 2005; Kline, 2015). The rotated solution yielded four interpretable factors, each accounting for variance in scores: Factor 1 (19%), Factor 2 (19%), Factor 3 (10%), and Factor 4 (10%). RMSEA = 0.13 (90% CI [.116, .153]). The factor solution and standardized loadings are shown in Table 1. Factor correlations are presented in Table 2. Overall, the analysis revealed clear primary loadings for most tests along with some notable cross-loadings, particularly with WAIS Coding, which spanned both visual attention and working memory domains.

In order to address the potential limitation of a higher degree of missingness of the PASAT 2" and PASAT 3" variables, the EFA was run on the raw, un-imputed data. Results of this analysis were similar to what was found in this analysis, in that four factors emerged, with each variable loading onto the same respective factors. Interestingly, Digit Span had significantly lower loadings when using the raw data, with a loading of .29 on Factor 2, and .22 on Factor 1. However, given the parallel findings with imputed versus raw data, only results with the imputed data were reported.

Factor 1 was named *Visual Attention/Psychomotor Speed* due to the main inclusion of tasks that assess visual processing and psychomotor abilities. The NAB A Efficiency test loaded most strongly on this factor with a high loading of 0.97, which indicated a significant association with visual attention and psychomotor speed. Additionally, the NAB D Efficiency also showed a substantial loading (0.76), followed by NAB B Efficiency (0.63) and NAB C Efficiency (0.50). WAIS Coding also loaded significantly on this factor (0.48), but notably, it exhibited some cross-loading on Factor 2 ("Auditory Attention/Working Memory") with a coefficient of 0.37, indicating its involvement in working memory processes.

Factor 2 was named *Auditory Attention/Working Memory* as it is primarily characterized by tests that involve auditory processing and working memory capabilities. The PASAT 2" had the strongest loading on this factor (0.84), closely followed by the PASAT 3″ (0.78), which implied these tasks were highly representative of auditory attention and working memory. The WAIS Arithmetic subtest also loaded prominently on this factor (0.68), confirming its relevance to working memory assessment. Interestingly, the NAB A Errors also showed notable loading on this factor (0.42).

Factor 3 was named *Visuospatial Scanning/Search* due to capturing tests that predominantly involve visuospatial scanning and searching tasks. The Trail Making Test A demonstrated a very strong loading on this factor (0.96), making it the most representative test of visuospatial scanning abilities. Trail Making Test B also loaded on this factor (0.62), indicating that it too assessed visuospatial components along with other cognitive processes.

Factor 4 was titled *Interference Management,* as it highlighted a task that measured the ability to handle cognitive disruption or dual-task interference. The NAB D Disruption test had an extremely high loading of 0.89 on this factor, which signified a strong association with tasks requiring the management of disruptive elements. This factor also

Table 1. Factor analysis of neuropsychological measures of attention with mild traumatic brain injury patients.

	1	2	3	4
	Visual Attention/ Psychomotor Speed	Auditory Attention/ Working Memory	Visuospatial Scanning/ Search	Interference Management
WAIS Digit Span	0.15	**0.41**	0.03	0.03
WAIS Arithmetic	0	**0.68**	0.14	0.01
WAIS Coding	**0.48**	0.37	0.02	0.04
NAB A Eff.	**0.97**	−0.03	0.02	−0.25
NAB A Err.	0.03	**0.42**	−0.11	0.09
NAB B Eff.	**0.63**	0.17	−0.06	0.07
NAB C Eff.	**0.50**	0.14	−0.04	0.23
NAB D Eff.	**0.73**	0.03	0.03	0.56
NAB D Dis.	−0.13	−0.01	−0.01	**0.89**
PASAT 3″	0.01	**0.78**	0.00	0.02
PASAT 2″	−0.05	**0.84**	−0.05	−0.07
TMT-A	0.02	−0.03	**0.96**	0.01
TMT-B	−0.10	0.13	**0.62**	−0.04

Note. WAIS = Wechsler Adult Intelligence Test IV; NAB A Eff. = NAB A Efficiency; NAB A Err = NAB A Errors; NAB B Eff. = NAB B Efficiency; NAB C Eff. = NAB C Efficiency; NAB D Eff. = NAB D Efficiency; NAB D Dis.= NAB D Disruption; PASAT 3″ = Paced Auditory Serial Addition Task, 3″; PASAT 2″ = Paced Auditory Serial Addition Task, 2″; TMT-A = Trail Making Test, Part A; TMT-B = Trail Making Test, Part B. Factor loadings < .10 are considered minimal and are often not interpreted. Correlations > .30 indicate moderate relationships, and correlations > .50 indicate strong relationships.

Table 2. Factor correlations.

	1	2	3	4
1. Visual Attention/ Psychomotor Speed	1.00	0.29	0.07	0.15
2. Auditory Attention/ Working Memory	0.29	1.00	0.11	0.10
3. Visuospatial Scanning/Search	0.07	0.11	1.00	−0.01
4. Interference Management	0.15	0.10	−0.01	1.00

captured some aspects of NAB D Efficiency (0.56), suggesting a connection between efficiency under regular and disrupted conditions.

As I used an oblimin procedure, the EFA reported permitted correlations between the four derived factors, which reflected the degree to which these factors are related to each other in the data. Factor 1 and Factor 2 (*Visual Attention/Psychomotor Speed* and *Auditory Attention Math/Working Memory*) had a correlation of 0.29, which suggested a moderate positive relationship. This indicated that while these factors were distinct, there was a level of shared variance between them, which could imply that some cognitive processes measured by these factors were related.

Factor 1 and Factor 3 (*Visual Attention/Psychomotor Speed* and *Visuospatial Scanning/Search*), as well as Factor 1 and Factor 4 (*Visual Attention/Psychomotor Speed* and *Interference Management*), showed weaker correlations, at 0.07 and 0.15, respectively. These low correlations suggested that the cognitive constructs measured by Factor 1 are relatively independent from those measured by Factors 3 and 4. This independence indicated distinct underlying cognitive domains with minimal overlap.

Factor 2 and Factor 3 (*Auditory Attention Math/Working Memory* and *Visuospatial Scanning/Search*), as well as Factor 2 and Factor 4 (*Auditory Attention Math/Working Memory* and *Interference Management*), also showed relatively low correlations of 0.11 and 0.10, respectively. Similar to Factor 1's relations, these findings suggested that Factor 2 measured cognitive aspects that were mostly distinct from those measured by Factors 3 and 4.

Factor 3 and Factor 4 (*Visuospatial Scanning/Search* and *Interference Management*) exhibited an almost negligible correlation of −0.01, which indicated no meaningful relationship between these two factors. This further emphasized that the cognitive constructs they measured were quite independent of each other.

Overall, the moderate to low correlations indicated that the factors captured different aspects of cognitive functioning, with some overlap particularly between Factors 1 and 2. Those factors therefore may involve related, but distinct cognitive processes. Nonetheless, the low associations between factors confirms the importance of considering multiple attentional processes in mTBI patients.

Discussion

This study aimed to investigate the factor structure of attention in individuals who have sustained mild traumatic brain injuries (mTBIs), employing a comprehensive battery of neuropsychological tests. Based on converging evidence from the theoretical considerations and a scree plot, four factors emerged from the data, contrary to the hypothesis of five factors. These four factors identified were labeled as 1) visual attention/psychomotor speed, 2) visual scanning/search, 3) auditory math/working memory, and 4) interference management. Despite the initial hypothesis being unsupported, findings are consistent with Mirsky's previous conceptualization of attention as being composed of specific, separate components (Mirsky, 1991).

The first factor was comprised of NAB A Efficiency, NAB B Efficiency, NAB C Efficiency, NAB D Efficiency, and WAIS Coding. This convergence of tests on a single factor suggested that they shared underlying cognitive and methodological commonalities, which likely reflected a composite construct related to both visual attention and psychomotor speed. These tests, all administered using pen and paper, inherently assess the integration of cognitive processing with motor responses. Critically, the tasks require participants to not only process visual information serially and swiftly but to also execute responses physically by writing or marking, which assesses psychomotor abilities. This requirement for visuomotor integration (i.e., coordinating visual inputs with motor outputs effectively) appeared to be a central underlying component of this factor. Such a skill is vital for activities where quick visual assessment needs to be followed by immediate physical action. Moreover, the format and administration of these tests (i.e., pen-and-paper) likely contribute significantly to their grouping under the same factor. This mode of response not only places a premium on psychomotor speed but also on the precision and accuracy of the responses, thus potentially defining this factor as one of visuomotor efficiency. This efficiency did not merely reflect the speed of cognitive or motor execution but rather a blend of both, where accuracy is equally paramount.

These findings align with previous research by Wu et al. (2020), which emphasized the importance of motor speed in cognitive processing following mild traumatic brain injury, underscoring that cognitive assessments often inadvertently measure motor speed alongside targeted cognitive functions due to the nature of test administration. In contrast, a test like the Finger Tapping Test (FTT), where the participant taps a key and the number of taps is recorded over five 10-second trials would be a measure more exclusively related to manual dexterity (Reitan & Wolfson 1985). Moreover, this factor grouping suggested a more integrated view of psychomotor efficiency than traditionally acknowledged in neuropsychological assessments. This perspective challenges some of the existing literature which may have previously categorized similar tests under purely cognitive or purely motor domains. For example, studies like those by Zgaljardic and Temple (2010a) which focus on cognitive deficits post-TBI might not fully account for the motor aspects implicit in cognitive test performance. In the initial hypothesis, the NAB Numbers and Letters Test and PASAT was expected to load across multiple factors, including divided attention and processing speed. However, the results showed that the first factor grouped NAB Parts A, B, C, and D Efficiency tests along with WAIS Coding, suggesting a convergence on a shared construct related to visuomotor integration and psychomotor speed. This result differs from the hypothesis, as these tests are grouped into a single factor rather than spreading across multiple cognitive domains. This analysis adds to this dialogue by demonstrating that the accuracy and speed of responses are not merely byproducts of cognitive or motor abilities alone but are indicative of a composite construct where both elements are important. NAB D Efficiency cross-loaded at 0.56 on Factor 4 (Interference Management), despite its stronger loading on Factor 1

(Visual Attention/Psychomotor Speed) at 0.73. This suggests that while the test primarily measures visuomotor efficiency, it also taps into interference management processes. The cross-loading implies that NAB D involves elements of managing cognitive interference, likely due to its requirement for sustained attention and the ability to filter out distractions, in addition to its demands on psychomotor and visual processing.

The second factor was comprised of PASAT 2" and 3," WAIS Arithmetic, WAIS Digit Span (DS), and NAB A Errors. In the initial hypothesis, it was predicted that tests such as Arithmetic and Digit Span would load onto a distinct "Working Memory" factor, while the PASAT was expected to cross-load onto both "Divided Attention" and "Working Memory" factors due to its reliance on multiple cognitive processes. This grouping can be fundamentally attributed to their auditory delivery and the engagement of specific cognitive abilities centered on working memory and numerical processing. First, the auditory mode of administration that characterizes these tasks is critical in assessing how information processed through auditory channels impacts attention within a mTBI population. These tests require participants to process, retain, and manipulate numerical information in real-time. Moreover, the mathematical and sequential reasoning demands common to these tests provide another layer of cognitive integration. For example, the PASAT challenges individuals to add sequences of numbers rapidly announced, necessitating active engagement with working memory. Similarly, the WAIS Arithmetic test assesses the ability to solve spoken mathematical problems without the aid of written calculations, thereby testing arithmetic reasoning alongside working memory for multiple problem components. DS, which involves repeating back a series of numbers (though not mathematical beyond counting) similarly taxes the ability to sequentially organize and recall auditory information. This convergence of auditory processing, memory load, and numerical reasoning on a single factor suggested that these cognitive processes are likely supported by overlapping mechanisms. Such mechanisms would facilitate the simultaneous processing of auditory inputs and the execution of complex cognitive tasks involving memory and calculation. Additionally, this finding is supported by a previous study in which patients who had experienced mTBI were found to have impaired performance on DS and the PASAT compared to other measures of attention (Wu et al., 2020).

In the introduction, it was posited that the DS and Arithmetic subtests might emerge as their own distinct factor rather than conventional measures of attention. These results offer a view that both supports and challenges this initial hypothesis. DS loaded significantly on the "Auditory Attention/Working Memory" factor, reinforcing views that regard DS as a measure of attentional and working memory capacities. However, DS had the lowest loading on this factor (.41). A reason for this could be attributed to the level of cognitive demand required for each task in this factor. DS assesses aspects of working memory and attention, primarily measuring the capacity to retain and reproduce a sequence of digits in the order presented (forward) or reverse (backward). This might be considered a more basic or foundational level of working memory compared to the tasks required by the PASAT and Arithmetic tests, which involve more complex processing, such as continuous updating, manipulation, and calculations in real-time. The PASAT, for example, not only tests memory span but also the ability to process and update information dynamically, making it cognitively more demanding (Gronwall, 1977). These explanations suggest that while DS is a valid measure of certain types of memory and attention, its specific characteristics and simpler cognitive demands compared to more complex tests like PASAT and Arithmetic might result in it having lower loadings on a factor characterized by broader and more intensive cognitive processes. These results support the former findings from Groth-Marnat and Baker (2003) which identified DS as a statistically significant, but weaker predictor of attentional abilities compared to other measures.

In the present factor analysis, the presence of NAB A Errors loading onto the second factor was surprising, as it does not appear to share the same characteristics of the other tasks. NAB A Errors specifically measures the frequency of errors, which can either mean "omission" errors, where a participant misses an "X" during the task in which they are meant to cross out all of the X's, or "commission" errors, where one mistakenly crosses through another letter or number in the row. These errors can be an indicator of lapses in attention or failures in error monitoring processes. Error monitoring is an executive function that involves the prefrontal cortex, similar to the regions involved in working memory and cognitive control utilized by the other three tasks (Miller & Cohen, 2001; Simões-Franklin et al., 2010). Tasks like the PASAT and Arithmetic inherently require a high level of accuracy and often self-correction as part of their execution, aligning them with the error detection and correction processes measured by NAB A Errors. The ability to monitor one's own performance and adjust it in real time is a shared skill across all these tasks (Barbey et al., 2011; Pietrzak et al., 2007; Sommer et al., 2021).

Contrary to the initial hypothesis, Digit Span did not load as a separate factor. However, it is possible that certain limitations of the study contributed to this finding. Treviño et al. (2021) posited that WAIS Digit Span should not be considered an accurate measure of attention after it loaded onto a separate factor with WAIS Arithmetic in their factor analysis. However, Treviño's study used Digit Span individual subscale scores (i.e., Digit Span Forward and Backward) in their analysis. For this analysis, the scaled score of the full Digit Span test was used, which may have contributed to the task loading onto the same factor as other similar tests. This supports the literature by Mirsky (1991) who used the full Digit Span scaled score in their analysis as well and achieved similar results. In the work of Mirsky (1991), the use of the full Digit Span scaled score (rather than separate subscale scores for forward and backward spans) may have influenced how the test clustered with other cognitive tasks during factor analysis. Mirsky found that when considering Digit Span as a whole, it reflected broader cognitive abilities beyond simple auditory or working memory, potentially contributing to its loading alongside tasks that assess similar constructs. This is consistent with the fact that factor analysis results can vary depending on the specific measures included in the analysis. Essentially, factor analysis works to pinpoint commonalities across various measures, but the nature of these commonalities is influenced by the range of included variables. Thus, what is identified as shared variance is contingent upon the scope of measures analyzed.

In this study, using the scaled score for the full Digit Span test, similar to Mirsky's approach, likely influenced its loading behavior. This methodological choice may have smoothed over the distinctions between forward and backward tasks, which might have different cognitive underpinnings, with forward span being more reflective of simple short-term memory and backward span requiring more complex working memory processes (Kessels et al., 2008). This could have led to a scenario where Digit Span aligns more closely with tests measuring a mix of memory and attention functions, as observed.

The fact that Digit Span had the lowest interpretable loading on its factor suggests that while it shares some commonality with other tests in that factor, its contribution to the factor is weaker, indicating a potential divergence in the cognitive constructs being measured. This subtlety aligns with findings from both our study and Mirsky's, supporting the notion that Digit Span as a composite score taps a blend of cognitive processes that are not purely about memory or attention but a mixture of both. As Mirsky found that Digit Span as a whole reflected broader cognitive abilities beyond simple auditory or working memory, it is possible that if the individual subtests (Digit Span Forward, Backward, and Sequencing) were separated, they would have different factor loadings. The correlation between Factor 1 (Visual Attention/Psychomotor Speed) and Factor 2 (Auditory Attention/Working Memory) was 0.29, indicating a moderate positive relationship between these two constructs. This suggests that while they assess distinct cognitive domains, there is some overlap, likely due to the shared attentional demands required for both visual and auditory tasks. The moderate correlation may also reflect the integration of attention with both motor and memory functions in tasks requiring real-time cognitive processing, such as responding to visual stimuli or retaining and manipulating auditory information.

The third factor included Trail Making Tests A and B, which is not entirely surprising considering Groff and Hubble found the TMT to not be a measure of a single cognitive domain but rather reflects a mix of processing speed, visual search, and executive functioning. In the initial hypothesis, it was expected the Trail Making Test (TMT) to load onto the "Selective Attention" and "Processing Speed" factors, given its demand on both visual scanning and rapid response execution. A principal components analysis with TBI patients also found TMT-A and TMT-B to be nonspecific measures of processing speed, executive functioning, and cognitive flexibility (Ríos et al., 2004). This lack of specificity in what the TMT measures supports the view that its results should not be interpreted as definitive evidence of impairment in any one particular cognitive area, such as attention or visuospatial search alone. A lower score on these tests can indicate cognitive challenges a person may be experiencing; however, we cannot say definitively that attention is the affected domain (Sánchez-Cubillo et al., 2009).

The fourth factor included one variable, NAB D Disruption, and had virtually no correlation with the other three factors. This score, calculated by dividing a ratio of Part D Efficiency (involving complex multitasking requirements of crossing out the "X's" while simultaneously adding numbers) by Part A Efficiency (a simpler task of only crossing out the "X's"), highlights the cognitive impact of increased task complexity. Its emergence as an isolated factor underscores its sensitivity to specific cognitive disruptions, particularly those involving the management of divided attention, which is often impacted by conditions such as mTBI (Lezak et al., 2012). The distinctiveness of the NAB D Disruption factor, showing virtually no correlation with other cognitive domains, aligns with the notion that complex attentional demands and multitasking are cognitive functions that can be specifically impacted in individuals with mTBI. This is supported by past literature, which emphasizes that factor analyses often reveal the specific cognitive profiles characteristic of the population being studied. For instance, Wu et al. (2020) found that mTBI patients performed normally on tasks of sustained attention and selective attention but were impaired in the areas of divided attention and information processing speed.

This exploratory factor analysis revealed a distinction between auditory and visual attention mechanisms. This separation aligns with the hypotheses and the current theories of attention, suggesting that attentional processes are not monolithic but rather encompass distinct auditory and visual domains. This finding corroborates the existing literature, including Mirsky's (1991) model of attention, which posits four components of attention (*focus, sustain, shift,* and *encode*) conceptualized with a focus on differentiating processes rather than sensory modalities. These findings add to the literature by providing empirical support that attention is multidimensional and involves distinct processes that can be separately influenced and measured. For instance, Mirsky's (1991) model emphasizes different aspects of attention without strictly binding them to a particular sensory modality. In Mirsky's framework, the Letter Cancelation and Digit Symbol tests revealed a 'Focus' component, which aligns with how these tasks loaded in the 'Visual Attention and Psychomotor Speed' factor. The Letter Cancelation Task is a similarly administered task to the NAB N&L Test, in which a participant is required to cross out letters on a page. However, these results diverge from Mirsky's findings in that TMT-A and TMT-B loaded onto a separate factor. These results also revealed a distinction between auditory and visual modalities of test administration, which is another divergence from previous research. Reasons for these differences could rest in the populations assessed; Mirsky recruited 203 participants with heterogeneous psychiatric and neurological diagnoses, a significant number of healthy volunteers, and nine individuals with head injuries but did not provide greater detail on participants. According to Fabrigar et al. (1999), the factor structure identified through exploratory factor analysis is understood to reflect the population being studied, emphasizing that statistical methods reveal dimensions that are specific to the dataset and reflective of the sampled individuals' characteristics and what measures are used. Details on what tests previous studies used in comparison to the current study can be found in Table 3.

Furthermore, the emergence of a visuospatial scanning/search factor distinct from other attentional constructs underscores the potential for these processes to be interpreted as unique cognitive components. This is primarily represented by TMT-A and TMT-B, supports and extends findings from Treviño et al. (2021), who also used found these tests to emerge in a broader 'Search' factor that included visual search tasks and Coding. These findings, however, separated the Trail Making Tests into their own factor; they had a weak correlation with the visual Attention and Psychomotor Speed factor (.07) which suggests that in this population they are tapping into different processes. A reason for this could be that Factor 1 primarily reflects visuomotor integration and processing speed, requiring individuals to rapidly process visual stimuli and execute fine motor responses with precision. These tasks emphasize automaticity and fluency in cognitive-motor coordination where speed is a critical performance component. In contrast, Factor 3 represents visual scanning and search efficiency, as assessed by the Trail Making Tests (TMT-A and TMT-B). These tasks involve higher-order cognitive control mechanisms, including cognitive flexibility, set-shifting, and sequencing, rather than pure motor speed. The demands of Factor 3 tasks are less about rapid motor execution and more about visuospatial tracking and strategic planning, making them more reliant on executive functions and attentional control rather than just psychomotor speed. Additionally, the isolation of a factor dedicated to 'Interference Management,' chiefly characterized by the NAB D Disruption score, highlights the importance of executive control and attentional regulation in managing complex task demands. This aligns with the 'Shift' component in Mirsky's model, where the ability to manage and adapt to changing task requirements is a necessary requirement of the Wisconsin Card Sorting Task (Kohli & Kaur, 2006).

Table 3. Factor analyses and corresponding tests from key studies.

Study	Factor	Tests Used
Mirsky (1991)	*Focus*	Stroop, **Coding (Digit Symbol)**, **TMT-A, TMT-B**, Letter Cancelation
	Sustain	CPT
	Shift	WCS
	Encode	**Arithmetic, Digit Span**
Schmidt (1994)	*Scanning*	Stroop, **Coding (Digit Symbol), TMT-A, TMT-B**
	Spanning	**Digit Span**, Visual Span
Treviño et al. (2021)	*Capacity*	MOT, Spatial Span, Visual Working Memory, **Coding (Digit Symbol)**
	Search	**TMT-A, TMT-B, Coding (Digit Symbol)**, Visual Search, Stroop
	Sustained	CPT
	Digit Span	**Digit Span**
	Arithmetic	**Arithmetic**
Results of Current Study	*Visual Attention and Psychomotor Speed*	**Coding (Digit Symbol)**, NAB A Eff., NAB B Eff., NAB C Eff., NAB D Eff.
	Auditory Attention and Working Memory	**Digit Span, Arithmetic**, NAB A Err., PASAT 2″, PASAT 3″
	Visuospatial Scanning and Search	**TMT-A, TMT-B**
	Interference Management	NAB D Dis.

Note: Bolded tests overlap with the current study. NAB A Eff. = NAB A Efficiency; NAB A Err = NAB A Errors; NAB B Eff. = NAB B Efficiency; NAB C Eff. = NAB C Efficiency; NAB D Eff. = NAB D Efficiency; NAB D Dis.= NAB D Disruption; PASAT 3″ = Paced Auditory Serial Addition Task, 3″; PASAT 2″ = Paced Auditory Serial Addition Task, 2″; TMT-A = Trail Making Test, Part A; TMT-B = Trail Making Test, Part B; WCS = Wisconsin Card Sorting; CPT = Continuous Performance Test; MOT = Multiple Object Tracking.

The traditional classifications of attention, such as sustained attention, divided attention, selective attention, and working memory by Mirsky (2009) could be conceptually mapped onto the factors identified in this study to provide a theoretical framework for interpreting attentional deficits following mTBI. Sustained attention, which refers to the ability to maintain cognitive focus over an extended period, aligns most closely with Factor 1 (Visual Attention/Psychomotor Speed). The tests within this factor, WAIS Coding and NAB Efficiency measures, require participants to engage in continuous, rapid processing of visual stimuli while executing motor responses, reflecting attentional persistence over time. This ability to maintain a consistent level of cognitive engagement and response execution is a hallmark of sustained attention. Similarly, selective attention, which requires individuals to focus on relevant stimuli while ignoring distractions, aligns with some of the task requirements in this factor.

In contrast, divided attention, which involves the capacity to allocate cognitive resources across multiple simultaneous tasks, corresponds to Factor 4 (Interference Management). The NAB D Disruption score, which loaded onto this factor, measures the ability to manage cognitive interference and sustain task performance under conditions of increased attentional load. Given that divided attention is fundamentally concerned with filtering out competing stimuli and maintaining task engagement across multiple cognitive streams, the processes underlying interference management are likely to be integral to divided attention functioning in individuals with mTBI.

Working memory, often conceptualized as an executive control function involving real-time information processing and manipulation, is most closely associated with Factor 2 (Auditory Math/Working Memory). This factor includes tests such as the Paced Auditory Serial Addition Test (PASAT), WAIS Arithmetic, and WAIS Digit Span, all of which require participants to hold and manipulate auditory or numerical information under time constraints. These tasks place significant demands on controlled attention, as they require the continuous updating, monitoring, and retrieval of information while suppressing irrelevant data. Additionally, attentional flexibility, a subset of executive attention related to the ability to shift focus and adapt to changing cognitive demands, aligns with Factor 3 (Visual Scanning/Search). The presence of TMT-B within this factor underscores its role in cognitive flexibility, as this task requires alternating between different visual targets and cognitive sets, which reflects the capacity to regulate and shift attentional control efficiently.

Clinical implications

The findings of this study underscore the importance of clinical judgment when assessing attention in individuals with mild traumatic brain injury (mTBI). While measures like Digit Span may capture basic aspects of auditory attention, their utility should be interpreted within the broader context of a patient's cognitive profile, clinical history, and observed behavior during testing. For instance, patients may perform adequately on simpler tasks but struggle with those requiring higher cognitive load and deficits may be missed if scores are interpreted in isolation. Similarly, performance on the Trail Making Test, particularly Part B, should be evaluated alongside other executive function measures to accurately localize deficits. These nuances highlight the need for a multidimensional and individualized approach to assessment and intervention.

This study's identification of relatively distinct auditory and visual attention components has important diagnostic and therapeutic implications. The low inter-factor correlations and simple structure of most tests suggest that these measures assess non-redundant cognitive processes, providing clearer targets for clinical decision-making. Clinicians are encouraged to use comprehensive test batteries that evaluate specific domains such as visual scanning, psychomotor speed, or auditory working memory, rather than relying on single global measures. Tailoring interventions to a patient's specific attentional profile, for example, focusing therapy on visual attention when visual deficits are prominent, can improve rehabilitation outcomes. This specificity aligns with literature supporting targeted cognitive rehabilitation (Allen, 2019) and reinforces the need to regularly assess both auditory and visual attention throughout the recovery process. Ultimately, understanding the multifaceted nature of attention in mTBI allows for more precise assessment, diagnosis, and treatment, leading to more personalized and effective clinical care.

Limitations and impact

The study faced several limitations, including the composite nature of Digit Span scores, whereas previous factor analyses used individual subscale scores. The use of a composite Digit Span score, rather than individual subtest scores, reflects standard clinical practice at the data collection site and the reporting conventions of many standardized assessments. However, this approach differs from some prior research, and future studies are encouraged to examine the factor structure of attention using separate Digit Span components to allow for greater differentiation of underlying cognitive constructs. Additionally, the cross-sectional design limits causal inferences. Participants in this type of study self-selected to come to a private practice clinic, which could introduce self-selection bias into the sample and the data may not be representative of the general population. Relatedly, this study only included participants who chose to be evaluated for mTBI, which limits understanding of those who would choose not to be evaluated. The ACRM revised criteria for diagnosing mTBI in 2023. While the updated 2023 criteria was still likely met for participants, it is important to note that data was collected before the 2023 criteria revision. As this study used archival data, not all participants were eligible for analysis as not all patients received every assessment measure outlined in this study. Additionally, a limitation is the lack of a standardized order of test administration, as the sequence varied depending on clinical considerations and patient needs; while this reflects real-world clinical practice, it may have introduced uncontrolled variability in performance.

Another limitation of the current study is the absence of data on participants' general intellectual functioning and activities of daily living (ADL) status. While such information would enhance the interpretability of the sample and provide important context for understanding attentional performance, these variables were not consistently available across the full archival dataset and were therefore not included in the analysis. Future research should aim to incorporate measures of cognitive baseline and functional status to strengthen both the theoretical significance and clinical applicability of findings in mTBI populations.

While best practices in EFA were followed, including appropriate sample size, assumption checks, and multiple factor retention criteria, the generalizability of the results would benefit from replication in other clinical mTBI samples using consistent test batteries

Additionally, many individuals who experience mTBI also experience other physical and emotional sequelae, such as depression, anxiety, and pain (Ponsford et al., 2011). These emotional disorders are not only common in mTBI populations but are also well-known for their disruptive effects on cognitive function, including attention. Anxiety, for example, can lead to difficulties in concentrating and increased distractibility, which might be misconstrued as a direct symptom of brain injury rather than a psychological response to the trauma or the stress of recovery. The differentiation of the direct cognitive effects of mTBI from these intertwined physical and emotional factors is rarely straightforward, as the co-occurrence of cognitive and emotional/physical symptoms post-mTBI is the norm rather than the exception. The potential overlap in symptoms attributable to physical pain, emotional distress, and primary neurological damage from the brain injury itself complicates the clear delineation of causality and can obscure the specific cognitive impacts of the neural trauma and adds a limitation to these findings (Carroll et al., 2020). Future studies should aim to address these limitations by incorporating longitudinal designs, exploring alternative measures, and enhancing the representativeness of the clinical sample.

A final limitation of this study relates to the potential impact of the COVID-19 pandemic on data collected between 2018 and 2023. Although there is no direct evidence of systematic differences in the dataset attributable to the pandemic, it is possible that pandemic-related factors, such as heightened psychological stress, altered healthcare access, and changes in patient referral patterns, may have introduced unmeasured sources of variance. These contextual influences could have subtly affected neuropsychological performance, clinical presentation, or testing conditions during this time period. Future research would benefit from examining potential differences in attentional profiles by comparing pre- and post-pandemic subsamples to better understand any pandemic-related effects on cognitive assessment outcomes in individuals with mTBI.

Conclusion

This study makes several contributions to the field of neuropsychology, particularly in understanding attention among mild traumatic brain injury (mTBI) patients. Through exploratory factor analysis, I identified four factors: visual attention/psychomotor speed, auditory attention/working memory, visuospatial scanning/search, and interference management. These findings highlight the complexity of attentional processes and emphasize the importance of using comprehensive assessment batteries to capture these multifaceted attentional deficits in mTBI populations. This study also expands on the role of visuomotor integration and auditory processing in evaluating attention, which may impact both clinical diagnostic tools and targeted rehabilitation strategies for individuals with mTBI.

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