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Critical Review

Working memory multicomponent model outcomes in individuals with traumatic brain injury: Critical review and meta-analysis

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Abstract

Objective: Traumatic Brain Injury (TBI) often leads to cognitive impairments, particularly regarding working memory (WM). This meta-analysis aims to examine the impact of TBI on WM, taking into account moderating factors which has received little attention in previous research, such as severity of injury, the different domains of Baddeley's multi-component model, and the interaction between these two factors, as well as the interaction with other domains of executive functions. **Method:** Following Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines, a systematic review and meta-analysis searched Google Scholar, PubMed, and PsycNET for studies with objective WM measures. Multiple meta-analyses were performed to compare the effects of TBI severity on different WM components. Twenty-four English, peer-reviewed articles, mostly cross-sectional were included. **Results:** TBI significantly impairs general WM and all Baddeley's model components, most notably the Central Executive ($d' = 0.74$). Severity categories, mild-moderate and moderate-severe, were identified. Impairment was found across severities, with "moderate-severe" demonstrating the largest effect size ($d' = 0.81$). Individuals with moderate-severe TBI showed greater impairments in the Central Executive and Episodic Buffer compared to those with mild-moderate injury, whereas no such differences were found for the Phonological Loop and Visuospatial Sketchpad. **Conclusions:** These findings enhance our understanding of WM deficits in varying severities of TBI, highlighting the importance of assessing and treating WM in clinical practice and intervention planning.

Keywords: Cognitive disorders; phonological loop; visuo-spatial sketchpad; central executive; episodic buffer; executive functions

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Introduction

Traumatic brain injury (TBI) causes a wide range of emotional, behavioral and cognitive impairments (Andelic et al., 2010; Azouvi et al., 2017), particularly in the domain of memory (Vakil, 2005), and executive functions (EF) (Jourdan et al., 2016; Ruet et al., 2018). Working memory (WM), defined as a control cognitive process, including a limited-capacity system responsible for temporary maintenance and storage of information, is one memory domain greatly affected by TBI (Dunning et al., 2016).

There are several WM models, however the most cited is the multicomponent model of Baddeley and Hitch (Baddeley, 2003; Baddeley et al., 2018; Baddeley, 2000; Baddeley & Hitch, 1974), including four components: Central Executive, Phonological Loop, Visuo-spatial Sketchpad and the Episodic Buffer (Table 1). The Central Executive is responsible for simultaneous visual and verbal information storage, coordination and processing, as well as for attentional control (Baddeley & Della, 1996). The Phonological Loop and Visuo-spatial Sketchpad are two slave systems with limited capacity storage. The Phonological Loop stores short-term verbal or auditory material, including both storage and articulatory rehearsal components. The Visuo-spatial Sketchpad stores spatial or visual information.

The Episodic Buffer is the last WM component presented in the extended model (Baddeley, 2020). It is responsible for integrating multi-modal information from all the latter three components with long-term memory (both semantic and episodic) and reconstructing multi-modal representation. In contrast to the other components, it has been much less studied. A meta-analysis on WM in children after TBI found no study regarding the Episodic Buffer (Phillips et al., 2017).

WM in general has been argued to be supported by a network of brain regions, but relying mainly on the prefrontal cortex (D'Esposito, 2007). Research has demonstrated that in parallel, each WM component separately uses additional brain areas (Baddeley, 2020) (see Table 1 for more details). As WM and its components rely heavily on the frontal lobes, it is to be expected that after TBI, WM functioning will be greatly compromised, due

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Table 1. Components of Baddeley's Working Memory model. The table presents the main functions of each one of the four components of the model, of the main tasks used to assess each component, and of the corresponding brain areas

	Central Executive	Phonological loop		Episodic buffer
Function	Visuo-spatial sketchpad Control, processing and coordination of verbal and visual information; updating;			
Dual-tasking	Short-term storage of verbal or auditory information;			
Articulatory rehearsal				
Tasks	Short-term storage of visual and/or spatial information Manipulation tasks : backward spans; n-back; self-ordered pointing; dual task (Quak et al., 2015)	Integration with long-term memory; multimodal integration		
Backwards or Sequencing span tasks (visuo-spatial / Digit Span); Reading span; switching tasks	Verbal or auditory maintenance tasks (forward digit or verbal spans, immediate serial recall; item recognition task)	Visual or spatial maintenance tasks (visuo-spatial spans, serial immediate recall; item recognition task)	Sentence recall; cross-modal tasks (such as letter/word-location, names-faces)	
Related brain areas	Dorsolateral prefrontal cortex and parietal areas (Curtis & D'Esposito, 2003)	Posterior temporal and ventrolateral prefrontal cortex; inferior parietal lobe (Aboitiz & Garcia, 2010; Alloway et al., 2009)	Frontal lobe (inferior), occipital, parietal and temporal cortex (Müller & Knight, 2006; Wager & Smith, 2003).	Hippocampal and right inferior and middle temporal lobe; prefrontal regions (Richmond et al., 2022; Rudner & Rönnberg, 2008; Rudner et al., 2007; Twick & Levy, 2021).

to the vulnerability of prefrontal areas in this condition. Indeed, patients who sustained TBI have been found to perform worse compared to controls on a large variety of WM tasks, such as n-back (Sanchez-Carrion et al., 2008), dual-task (Allain et al., 2001; Asloun et al., 2008; Couillet et al., 2010), serial span (McAllister et al., 2004; Perlstein et al., 2004) and especially in tasks with high loads and pressure (Mangels et al., 2002; Withaar et al., 2000). Earlier studies have suggested that WM deficits are mainly due to impairment of the Central Executive component. For example, compared to a control group, patients with severe TBI were found to have only marginal impairments in slave system functioning, but a significant deficit in Central Executive (Vallat-Azouvi et al., 2007). This finding can be related to executive functioning deficits which are frequently observed after severe TBI (Kavé & Heinik, 2017; Larson et al., 2012). Indeed, Central Executive tasks are strongly related to executive functioning processes, particularly flexibility and shifting (Lehto, 2018), with mutual associations with the prefrontal cortex (Goldman-Rakic, 2012).

Recent systematic reviews and meta-analyses have examined the impairments of WM in individuals after TBI (Dunning et al., 2016; Phillips et al., 2015). However, findings were limited specifically in relation to the impact of different TBI severity on each of the model components (Bryer et al., 2013; Dunning et al., 2016; Forbes et al., 2009; Nee et al., 2013). The present study aims to deepen our understanding of WM impairments after TBI, while addressing these limitations.

The main research questions were as follows: (1) Which individual WM component (i.e., Central Executive, Phonological Loop, Visuospatial Sketchpad, or Episodic Buffer) is most affected following TBI? (2) Does the overall impairment in WM (ignoring individual components) vary as a function of TBI severity? (3) How do these two variables interact? In other words, are different WM subcomponents affected differently by injury severity (for example is the effect of injury severity larger on the Central Executive than on slave systems?). (4) Are Central Executive deficits related to more general deficits in EF? To address these questions, multiple meta-analyses were performed, using data retrieved from the relevant studies. First, we hypothesized that patients with TBI would demonstrate poorer WM functioning as compared to controls, regardless of injury severity and WM component. Second, we hypothesized that greater injury severity would have larger effects on WM functioning. Furthermore, based on previous studies (Vallat-Azouvi et al., 2007) we expected some WM subcomponents would be more sensitive to TBI than others: individuals with greater TBI severity were expected to have a greater deficit of the Central Executive with a less severe deficit in Slave Systems, compared to the less severely affected patients. By contrast, patients with mild to moderate TBI were not expected to present such a dissociation between the Central Executive and the Slave systems. We hypothesized this dissociation could be partially explained by greater executive functioning deficits after severe TBI. Lastly, as little research has been conducted on the Episodic Buffer, we did not have any a priori hypothesis regarding the effects of severity on this component.

Materials and methods

Literature search and selection criteria

The study was designed to summarize and synthesize research evidence appropriately, in order to inform proper practice and policy (Cook et al., 1997). We have developed the study protocol according to the guidelines of Preferred Reporting Items for

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Systematic Reviews and Meta-analyses Protocol (PRISMA-P) (Moher et al., 2009; Shamseer et al., 2015). In addition, the meta-analysis was prospectively registered with the PROSPERO International prospective register of systematic reviews (registration number: CRD42023397052).

Our study contained four stages: literature identification, screening, selection, and analysis. Literature selection was based on strict eligibility criteria, yielding a set of studies included in the present meta-analysis. Literature identification consisted of a vast literature search for papers published from January 1990 until January 2023. We used the Google Scholar, PubMed and PsycNET search engines to search within abstracts for the terms *Working memory AND TBI*. To better control publication bias, we searched Google Scholar for additional articles that may have been missed on the initial search. We also included the additional *Working memory multi-component, phonological loop, central executive, visuospatial sketchpad, episodic buffer* and *injury severity* search terms. All searches were conducted in English. Literature was also sourced from previously published literature reviews, including the aforementioned published literature reviews (Bryer et al., 2013; Dunning et al., 2016; Eierud et al., 2014; Iverson, 2010; Königs et al., 2016; Phillips et al., 2015; Rohling et al., 2011; Zhu et al., 2019). Following initial extraction, TBI severity was divided into two main categories: Mild-Moderate and Moderate-Severe. Ideally, we would have liked to have three distinct groups: Mild, Moderate, and Severe. Unfortunately, in all studies reviewed in this Meta-analysis, patient groups were categorized either as Mild-Moderate or Moderate-Severe. Though Moderate severity is included in both severity groups, it is reasonable to assume that the Moderate-Severe are more severely impaired than the Mild-Moderate group. Working Memory components were divided into four categories: Central executive, Phonological loop, Visuospatial sketchpad, and Episodic buffer. An additional domain of Executive function was also included. The rationale was to compare the effect of TBI on the Central Executive to its effect on other domains of EF, namely information generation (assessed with verbal fluency) and mental flexibility (assessed with tasks such as the Trail Making Test-B), which are assumed to be partly related, although independent of WM functioning. No Ethical Approval was needed for this study.

Inclusion criteria

The studies included had working memory outcomes tested on participants medically diagnosed with TBI (a change in brain function, or other evidence of brain damage/pathology by an external trauma or blow to the head, via brain imaging techniques; see Menon, Schwab, Wright, & Maas, 2010), with information about severity such as Glasgow Coma Scale (GCS), duration of post-traumatic amnesia (PTA), duration of loss of consciousness (LOC) and medical records based on clinical observation (Levin et al., 1988; Williamson et al., 2004). We included studies regardless of TBI cause, mechanism of injury and medication. All studies were in English and peer-reviewed, including adult participants in an age range of 20–65 (in order to control for the confounding effect of aging on cognition). The outcomes had to be examined as the effect of TBI on at least one of the four distinct aforementioned WM components of Baddeley's WM model (Baddeley, 2000). Additionally, the outcomes had to be measured by objective and validated neuropsychological tests or paradigms. In an attempt to ensure that we are including in each test category compatible tests, valid tests and paradigms were either standardized tests or clearly described paradigms, reflecting specifically the studied WM component. Papers included utilized normative data or statistical information which could be used to generate statistical analysis of group difference through effect size (*d*-value). All studies must also have included a control group/comparison group with matched cases and controls on age, education and gender. To this end, we included both longitudinal and cross-sectional designs, as the number of papers was limited.

Exclusion criteria

We did not include studies evaluating the effect of TBI on emotional, physiological or neurological functions. Additional excluded studies involved adults with TBI severity who did not report outcomes separately by severity, or studies with general WM score without scores of a distinct WM component or detailed assessment tool.

Meta-analysis procedure

From the primary and broad search terms we reviewed, 852 studies in English were retrieved. Studies in foreign languages and Duplications were removed (827) before narrowing down to studies with cognitive assessment of WM functions in distinct TBI severity (743 removed). The magnitude of search terms allowed us to ensure all relevant studies were identified, even if their abstract did not necessarily include WM or cognitive assessment as a keyword. Eighty-four publications which reviewed WM effects after TBI were identified and carefully reviewed. The majority of the eliminated studies did not have a separate WM component assessment or did not have a matched control group (by age, gender and education). Additional exclusion reasons included inability to access relevant data such as descriptive statistics or calculated effect sizes. Twenty-four studies were deemed to fulfill all inclusion and exclusion criteria (from unique publications). Because of the clinical sample, all studies used cross-sectional designs. Two studies also used longitudinal designs (Kumar et al., 2013; Sanchez-Carrion et al., 2008). Twenty-three studies recruited control groups of matched age, gender, and education. One study (Johansson et al., 2009) had two distinct TBI severity groups and an additional control group, thus the data from the control group were included twice (with just half the stated sample size). An additional study recruited matched comparison of distinct and varying TBI severity (Zimmermann et al., 2017). From each study, we calculated and included all significant and non-significant results. Three studies were included from analysis of previous meta-analyses and the rest were from additional searches. Asterisks in the reference section are used to identify studies included in the meta-analyses, and Figure 1 provides an overview of the search process.

Study characteristics

There were a total of 2114 participants across studies: 828 participants with TBI and 1286 controls. The average age at testing was 33.4 years, range 20.3–64.11. Gender breakdown was reported in all studies accept two (53% males).

The determination of TBI severity across studies was done using a single or a combination of indicators: GCS, duration of LOC, duration of PTA, medical examination. There were 14 studies with mild-moderate patients with TBI (462 participants) and 12 studies with moderate-severe patients with TBI (366 participants).

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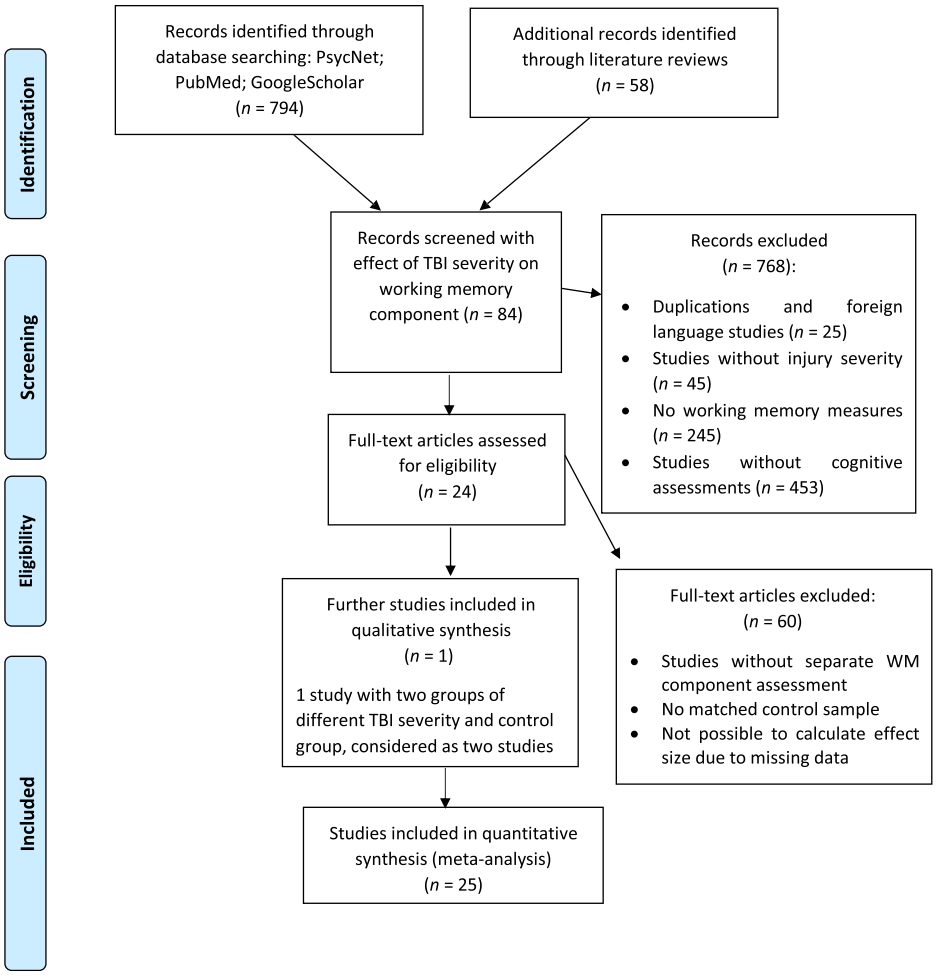

Figure 1. Flow chart of the literature search process according to Preferred Reporting Items for Systematic Reviews and Meta-analyses guidelines.

Eighteen studies (75%) reported the mean time since injury, which ranged from 0.17 to 31.56 years. Sixteen of these studies were cross-sectional. All studies recruited participants at variable lengths of time post injury. The two longitudinal studies examined participants at fixed time periods across the first 10 months post injury.

Quality assessment

The quality of the data in the included studies was assessed by two reviewers (BL and CVA), using the National Institutes of Health (NIH) quality assessment tools (NIH, 2014). NIH quality assessment tool was chosen as it is more comprehensive, thus enabling us an extensive quality assessment of all included studies.

Data coding

Statistical data was collected from each study including participant number, means, and *SD* for both groups. The results of each working memory test were categorized according to the WM component it tested.

Group means and *SD* of neuropsychological WM scores were recorded. If these studies included results of tests assessing executive function domain, they were also recorded.

In case a study had multiple scores for one WM component or executive functioning domain, we first extracted all the data and then chose the score of the most commonly cited tests for each measure. Thus, for each published study it was possible to have five effect sizes. Finally, for multiple effect sizes in a specific component or domain derived from equally relevant tests, the highest effect size was used reflecting the most robust effect (Lopez-Lopez et al., 2018). The following variables were included in a coding sheet: study identification number, study name and authors, year of publication, number of total participants, number of clinical and non-clinical participants with gender characteristics, TBI severity of clinical sample, number of participants in each group, age at testing, time from injury and age at injury, years of education, the mean age and age range of participants, language of testing, and which cognitive tests were used for each working memory component and executive functioning domain. We created a coding sheet with all tests and results, as well as for multiple test results for a single component. However, following the method detailed above we created a final coding sheet including one component score (*M* and *SD*) for each WM component or executive function tested within a single study. All data from the studies were extracted independently by the authors and coded. Inter-rater reliability was 100%. All data were extracted from papers.

Statistical analyses

Analyses of effect sizes were calculated according to Cohen (Cohen, 2013), due to usage of comparison groups with different

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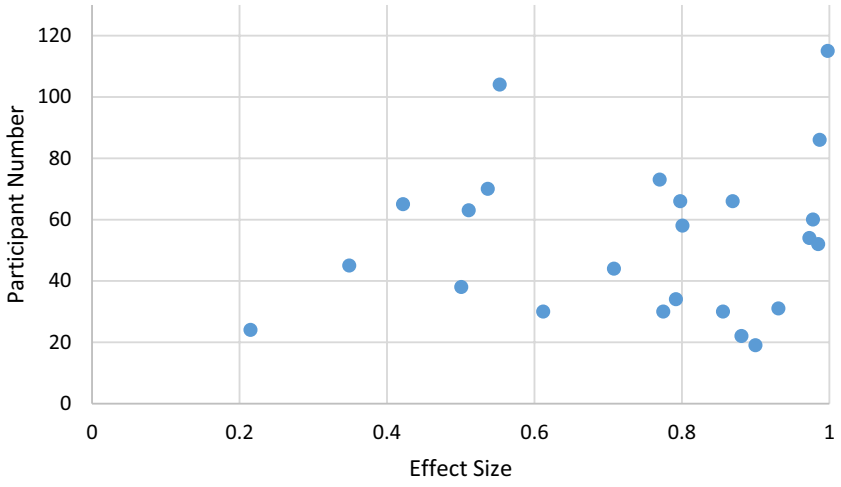

Figure 2. Funnel plot showing effect sizes for interventions delineated by sample size.

sample sizes, thus requiring us to weight the estimation of the sample sizes. Effect-size calculation was based on the recommended formula: mean clinical group minus the mean control group change divided by the pooled *SD* with a bias adjustment (Cohen, 2013). Effect-size calculations were first carried out using the "psychometrica" website (Lenhard, 2017) and then entered into an Excel sheet for total effect sizes and homogeneous effect calculations.

Studies with insufficient and missing data were excluded from the meta-analysis. Given the heterogeneity of TBI sample characteristics, and WM assessments within domains in the included studies, we chose a priori to use random-effects models (Field & Gillett, 2010).

Effect sizes were also calculated according to Rosenthal (1991). In order to assess homogeneity/heterogeneity, we examined the data using the *Q* test (Sanchez-Meca & Fulgencio, 1997; Shadish & Haddock, 1994) and I^2 (Higgins & Thompson, 2002). Accordingly, if the *Q* value was not significant, then the effect sizes were considered homogeneous, and the mean effect size was considered the best estimation for the data. However, if the *Q* is significant, moderators should be suggested, as the effect sizes were considered to be heterogeneous. Additionally, as *Q* test's ability to detect heterogeneity is limited, we combined the use of I^2 to determine the degree of heterogeneity. Alternatively, I^2 statistic quantifies the proportion of total variation among study results attributable to heterogeneity rather than sampling error. Higher I^2 values signify greater heterogeneity. Although there is no fixed threshold for interpretation, PRISMA guidelines suggest 0–25% indicates low heterogeneity; 25–50% implies moderate heterogeneity; 50–75% suggests high heterogeneity; and 75–100% indicates very high heterogeneity.

Results

Overall WM functioning

Our final meta-analysis included 24 studies and 25 distinct group comparisons, which yielded 66 effect sizes: 53 for the four WM components and 13 for executive functioning domain. Out of the WM components, the Central Executive was the most frequently assessed ($n = 20$). The Phonological Loop was assessed in sixteen studies ($n = 16$), the Visuo-spatial Sketchpad was assessed in 12 and the Episodic Buffer in five studies.

Initially the overall WM impairment in TBI was entered into a meta-analysis comprising all the published studies. The results indicated TBI participants had significantly poorer WM functioning than controls, with a medium-large effect size of 0.74. Results were deemed homogeneous, generating a *Q* value of 14.16, ($p < 0.05$) and $I^2 = 0$. A funnel plot of included studies did not show any asymmetry, an indication that significant publication bias was not likely (Figure 2).

Assessment of the different subcomponents of WM

Therefore, the second stage was to determine which WM component was most impaired following TBI, and whether each component could be categorized as having a homogenic, significant effect. Studies were divided into four meta-analyses reviewing the different WM components; all model components categories demonstrated moderating, homogeneous, and significant results. As can be seen in Table 2, the Central Executive component was affected most significantly, demonstrating the highest effect size of 0.74 ($df = 19$, 95% CIL = 0.51, 1.04, $Q = 12.13$, $p < 0.05$, $I^2 = 0$). The Episodic Buffer component demonstrated the lowest effect size of 0.49 ($df = 4$, 95% CIL = 0.07, 1.04); and was deemed homogeneous ($Q = 1.37$, $p < 0.05$, $I^2 = 0$). For both Slave system components, we have found moderate effect sizes: 0.64 for Phonological Loop component ($df = 15$, 95% CIL = 0.58, 0.86) and 0.54 for Visuo-spatial Sketchpad ($df = 11$, 95% CIL = 0.49, 0.89). Both were deemed to be homogeneous (Phonological Loop - $Q = 14.03$, $p<0.05$, $I^2 = 0$; $Q = 15.49$, $p < 0.05$, $I^2 = 29.0$).

Influence of injury severity

At the third stage, following comparison of WM deficits across the various components, we investigated the second factor: injury severity. Which severity level could be classified as having the largest WM deficits, regardless of WM component, and whether each severity could be classified as having a homogeneous effect? As in most studies, meta-analyses run on injury severity included Mild-Severe severity. When studies were separated into two meta-analyses reviewing the two levels of injury severity (Mild-Moderate TBI, $n = 14$; Moderate-Severe, $n = 12$), homogeneous results were generated. Moderate-severe injury severity demonstrated the greatest effect size, 0.80, ($df = 11$, 95% CIL = 0.51, 1.06), which was homogeneous across WM components ($Q = 8.72$, $p < 0.05$,

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Table 2. Effect size and methodology of studies sorted by working memory domains

Author	WM Model Component	Study design	Mean age & participants number	TBI (*n*)	Controls (*n*)	Time since injury (Years)	Education (Years)	Injury severity	Cognitive test	Effect size	
Ozen et al., 2013	Central Executive	Cross-Sectional	20.29 *n* = 34	17	17	5.6	14.76	Mild	3-Back, Response time	0.79	
Asloun et al., 2008	Central Executive	Cross-Sectional	28.6 *n* = 86	43	43	2.6	12.15	Severe	2-Back, Hit-rate	0.98	
Lepach et al., 2015	Central Executive	Cross-Sectional	41.21 *n* = 861	151	710	1.3	10.38	Mild-Moderate	BSCE index of mental control	0.774	
Dores et al., 2017	Central Executive	Cross-Sectional	28.38 *n* = 19	9	10	3.18	10.50	Severe	2-Back, Hit-rate	0.9	
Price, 2009	Central Executive	Cross-Sectional	44.35 *n* = 30	12	18	Nan	Nan	Severe	Spatial Span- backwards, correct	0.86	
Hanten et al., 2003	Central Executive	Cross-Sectional	30.1 *n* = 115	70	45	2.7	13.3	Severe	SOP (subhect ordered pointing) task, highest level completed	0.99	
Jurick et al., 2018	Central Executive	Cross-sectional	33.86 *n* = *70*	42	28	6.58	15.04	Mild	Digit Span- Backwards, correct	0.54	
Jak et al., 2020	Central Executive	Cross-sectional	33.25 *n* = 44	28	16	7.25	15.37	Mild	Combined Z-score of WM index, TMT 1, color-word interference- correct naming	0.49	
Coste et al., 2011	Central Executive	Cross-sectional	27.09 *n* = 66	33	33	0.89	13.86	Severe	Running Span, correct	0.87	
Coste et al., 2015	Central Executive	Cross-sectional	27.7 *n* = 30	15	15	3.42	13.4	Severe	Visuospatial Span- Backwards, correct	0.77	
Draper & Ponsford, 2008	Central Executive	Cross-sectional	42.14 *n* = 104	60	48	31.56	11.78	Moderate-Severe	Digit Span- Backwards, correct	0.55	
Konrad et al., 2011	Central Executive	Cross-sectional	36.85 *n* = 66	33	33	6.02	11.33	Mild	Digit Span- Backwards, correct	0.79	
Kumar et al., 2013	Central Executive	Longitudinal	29.25 *n* = 60	30	30	0.17	12.68	Mild	Sternberg Paradigm- Verbal d' (False alarm+ Hits)	0.97	
Johansson et al., 2009	Central Executive	Cross-sectional	43.6 *n* = 54	14	40	6.9	16.05	Mild	Digit Span- Backwards, correct	0.97	
Johansson et al., 2009	Central Executive	Cross-sectional	42.45 *n* = 52	12	40	11.1	15.1	Moderate-Severe	Digit Span- Backwards, correct	0.98	
Chen et al., 2012	Central Executive	Cross-sectional	35.75 *n* = 38	20	18	Nan	15.5	Mild	Digit Span- Backwards, correct	0.5	
Sanchez-Carrion et al., 2008	Central Executive	Longitudinal	24.21 *n* = 22	12	10	0.7	11.75	Mild	Digit Span- Backwards, correct	0.24	
McAllister et al., 2001	Central Executive	Cross-sectional	29.8 *n* = 30	18	12	Nan	14.45	Mild	3-Back, Hit-rate	0.11	
Palacios et al., 2011	Central Executive	Cross-sectional	23.65 *n* = 31	15	16	Nan	11.6	Severe	2-Back, Hit-rate	0.93	
Vallat-Azouvi et al., 2007	Central Executive	Cross-sectional	29.85 *n* = 58	30	28	4.29	11.9	Severe	Running Span task, correct	0.8	
									Central Executive Mean effect size	**0.74**	
Ozen et al., 2013	Phonological Loop	Cross-Sectional	20.29 *n* = 34	17	17	5.6	14.76	Mild	Digit Span- Forwards, correct	0.29	0.058
Asloun et al., 2008	Phonological Loop	Cross-Sectional	28.6 *n* = 86	43	43	2.6	12.15	Severe	Dual Task 1-Back, Hit-rate	0.99	0.46
Lepach et al., 2015	Phonological Loop	Cross-Sectional	41.21 *n* = 861	151	710	1.3	10.38	Mild-Moderate	Logical Memory 1 (WMS-4)- Immediate memory, correct	0.79	0.44
Zimmermann et al., 2017	Phonological Loop	Cross-Sectional	36.2 *n* = *65*	26	39	1.9	9.5	Moderate-Severe	Auditory word span, correct	0.42	
Coste et al., 2015	Phonological Loop	Cross-sectional	27.7 *n* = 30	15	15	3.42	13.4	Severe	Digit Span- Forwards, correct	0.7	
Draper & Ponsford, 2008	Phonological Loop	Cross-sectional	42.14 *n* = 104	60	48	31.56	11.78	Moderate-Severe	Digit Span- Forwards, correct	0.39	
Konrad et al., 2011	Phonological Loop	Cross-sectional	36.85 *n* = 66	33	33	6.02	11.33	Mild	Digit Span- Forwards, correct	0.79	
Kwok et al., 2008	Phonological Loop	Cross-sectional	39.16 *n* = 63	31	32	0.25	10.82	Mild	Auditory verbal learning test- Immediate recall, correct	0.51	
Kumar et al., 2013	Phonological Loop	Longitudinal	29.25 *n* = 60	30	30	0.17	12.68	Mild	Sternberg Paradigm- Verbal, correct	0.96	
Johansson et al., 2009	Phonological Loop	Cross-sectional	43.6 *n* = 54	14	40	6.9	16.05	Mild	Digit Span- Forwards, correct	0.47	
Johansson et al., 2009	Phonological Loop	Cross-sectional	42.45 *n* = 52	12	40	11.1	15.1	Moderate-Severe	Digit Span- Forwards, correct	0.95	
Chen et al., 2012	Phonological Loop	Cross-sectional	35.75 *n* = 38	20	18	Nan	15.5	Mild	Digit Span- Forwards, correct	0.2	
Sanchez-Carrion et al., 2008	Phonological Loop	Longitudinal	24.21 *n* = 22	12	10	0.7	11.75	Mild	Digit Span- Forwards, correct	0.88	
	Phonological Loop	Cross-sectional	29.8 *n* = 30	18	12	Nan	14.45	Mild	0-Back, correct	0.61	

Table 2. (*Continued*)

Author	WM Model Component	Study design	Mean age & participants number	TBI (*n*)	Controls (*n*)	Time since injury (Years)	Education (Years)	Injury severity	Cognitive test	Effect size	
McAllister et al., 2001											
Palacios et al., 2011	Phonological Loop	Cross-sectional	23.65 *n* = 31	15	16	Nan	11.6	Severe	Digit Span- Forwards, correct	0.47	
Vallat-Azouvi et al., 2007	Phonological Loop	Cross-sectional	29.85 *n* = 58	30	28	4.29	11.9	Severe	Letter span- Forwards, correct	0.72	
									Phonological Loop Mean effect size	**0.64**	
Ozen et al., 2013	Visuospatial Sketchpad	Cross-Sectional	20.29 *n* = 34	17	17	5.6	14.76	Mild	Digit-Symbol (WAIS-4), correct	0.45	0.058
Lepach et al., 2015	Visuospatial Sketchpad	Cross-Sectional	41.21 *n* = 861	151	710	1.3	10.38	Mild-Moderate	Visual WM index (WMS-4)	0.83	0.44
Zimmermann et al., 2017	Visuospatial Sketchpad	Cross-Sectional	36.2 *n* = *65*	26	39	1.9	9.5	Moderate-Severe	Trail Making-1, time	0.27	
Price, 2009	Visuospatial Sketchpad	Cross-Sectional	44.35 *n* = 30	12	18	Nan	Nan	Severe	Spatial Span- backwards, correct	0.78	
Spikman et al., 2012	Visuospatial Sketchpad	Cross-Sectional	30.05 *n* = 73	28	55	Nan	12	Moderate-Severe	Trail Making-1, time	0.77	
Coste et al., 2015	Visuospatial Sketchpad	Cross-sectional	27.7 *n* = 30	15	15	3.42	13.4	Severe	Visuospatial Span- Forwards, correct	0.63	
Draper & Ponsford, 2008	Visuospatial Sketchpad	Cross-sectional	42.14 *n* = 104	60	48	31.56	11.78	Moderate-Severe	Digit-Symbol (WAIS-4), correct	0.37	
Konrad et al., 2011	Visuospatial Sketchpad	Cross-sectional	36.85 *n* = 66	33	33	6.02	11.33	Mild	Trail Making-1, time	0.79	
Kumar et al., 2013	Visuospatial Sketchpad	Longitudinal	29.25 *n* = 60	30	30	0.17	12.68	Mild	Sternberg Paradigm- Visual, correct	0.29	
Johansson et al., 2009	Visuospatial Sketchpad	Cross-sectional	43.6 *n* = 54	14	40	6.9	16.05	Mild	Block Span- Forwards, correct	0.58	
Johansson et al., 2009	Visuospatial Sketchpad	Cross-sectional	42.45 *n* = 52	12	40	11.1	15.1	Moderate-Severe	Block Span- Forwards, correct	0.2	
Vallat-Azouvi et al., 2007	Visuospatial Sketchpad	Cross-sectional	29.85 *n* = 58	30	28	4.29	11.9	Severe	Block Span- Forwards, correct	0.54	
									Visuospatial Sketchpad Mean effect size	0.54	
Price, 2009	Episodic Buffer	Cross-Sectional	44.35 *n* = 30	12	18	Nan	Nan	Severe	Object Span- COAD (computerized object and abstract designs test)	0.77	
Coste et al., 2011	Episodic Buffer	Cross-sectional	27.09 *n* = 66	33	33	0.89	13.86	Severe	Short-term binding task (STB), correct maintenance score	0.48	
Coste et al., 2015	Episodic Buffer	Cross-sectional	27.7 *n* = 30	15	15	3.42	13.4	Severe	Short-term binding task (STB), correct maintenance score	0.66	
Belleville et al., 2006	Episodic Buffer	Cross-sectional	64.11 *n* = 45	28	17	Nan	14.6	Mild	Face-name association task, correct	0.35	
Monti et al., 2013	Episodic Buffer	Cross-sectional	22.35 *n* = 24	12	12	4	15.5	Mild	Face-name association task, correct	0.21	
									Episodic Buffer Mean effect size	**0.49**	0.96

Table 3. Effect size and methodology of studies sorted by injury severity categories

Author	Injury severity	Study design	Mean age & participants number	TBI (*n*)	Controls (*n*)	Time since injury (Years)	Education (Years)	Working Memory Model component	Cognitive test	Effect size
Ozen et al., 2013	Mild-Moderate	Cross-Sectional	20.29 $n = 34$	17	17	5.6	14.76	Central Executive	3-Back, correct	0.79
Lepach et al., 2015	Mild-Moderate	Cross-Sectional	41.21 $n = 861$	151	710	1.3	10.38	Visuospatial sketch pad	Visual WM index (WMS-4)	0.83
Zimmermann et al., 2017	Mild	Cross-Sectional	36.2 $n = 65$	26	39	1.9	9.5	Phonological Loop	Auditory word span, correct	0.42
Jurick et al., 2018	Mild	Cross-sectional	33.86 $n = 70$	42	28	6.58	15.04	Central Executive	Digit Span- Backwards, correct	0.54
Jak et al., 2020	Mild	Cross-sectional	33.25 $n = 44$	28	16	7.25	15.37	Central Executive	Combined Z-score of WM index, TMT 1, color-word interference- correct naming	0.49
Konrad et al., 2011	Mild	Cross-sectional	36.85 $n = 66$	33	33	6.02	11.33	Phonological Loop	Digit Span- Backwards, correct	0.79
Kwok et al., 2008	Mild	Cross-sectional	39.16 $n = 63$	31	32	0.25	10.82	Phonological Loop	Auditory verbal learning test- Immediate recall, correct	0.51
Kumar et al., 2013	Mild	Longitudinal	29.25 $n = 60$	30	30	0.17	12.68	Phonological Loop	Sternberg Paradigm- Verbal d' (False alarm+ Hits)	0.97
Johansson et al., 2009	Mild	Cross-sectional	43.6 $n = 54$	14	40	6.9	16.05	Central Executive	Digit Span- Backwards, correct	0.97
Chen et al., 2012	Mild	Cross-sectional	35.75 $n = 38$	20	18	Nan	15.5	Central Executive	Digit Span- Backwards, correct	0.5
Sanchez-Carrion et al., 2008	Mild	Longitudinal	24.21 $n = 22$	12	10	0.7	11.75	Phonological Loop	Digit Span- Forwards, correct	0.88
McAllister et al., 2001	Mild	Cross-sectional	29.8 $n = 30$	18	12	Nan	14.45	Phonological Loop	0-Back, correct	0.61
Belleville et al., 2006	Mild	Cross-sectional	64.11 $n = 45$	28	17	Nan	14.6	Episodic Buffer	Face-name association task, correct	0.35
Monti et al., 2013	Mild	Cross-sectional	22.35 $n = 24$	12	12	4	15.5	Episodic Buffer	Face-name association task, correct	0.21
									Mean effect size	**0.63**
Asloun et al., 2008	Severe	Cross-Sectional	28.6 $n = 86$	43	43	2.6	12.15	Phonological Loop	Dual-Task 1-back, correct	0.99
Dores et al., 2017	Severe	Cross-Sectional	28.38 $n = 19$	9	10	3.18	10.50	Central Executive	2-Back, correct	0.9
Zimmermann et al., 2017	Moderate-Severe	Cross-Sectional	36.2 $n = 65$	26	39	1.9	9.5	Phonological Loop	Auditory word span, correct	0.42
Price, 2009	Severe	Cross-Sectional	44.35 $n = 30$	12	18	Nan	Nan	Central Executive	Spatial span- Backwards, correct	0.85
Hanten et al., 2003	Severe	Cross-Sectional	30.1 $n = 115$	70	45	2.7	13.3	Central Executive	SOP (subhect ordered pointing) task, highest level completed	0.99
Spikman et al., 2012	Moderate-Severe	Cross-Sectional	30.05 $n = 73$	28	55	Nan	12	Visuospatial Sketchpad	Trail Making-1, time	0.77
Coste et al., 2011	Severe	Cross-sectional	27.09 $n = 66$	33	33	0.89	13.86	Central Executive	Running Span, correct	0.87
Coste et al., 2015	Severe	Cross-sectional	27.7 $n = 30$	15	15	3.42	13.4	Central Executive	Visuospatial Span- Backwards, correct	0.77
Draper & Ponsford, 2008	Moderate-Severe	Cross-sectional	42.14 $n = 104$	60	48	31.56	11.78	Visuospatial Sketchpad	Digit-Symbol (WAIS-4)	0.37
Johansson et al., 2009	Moderate-Severe	Cross-sectional	42.45 $n = 52$	12	40	11.1	15.1	Central Executive	Digit Span- Backwards, correct	0.98
Palacios et al., 2011	Severe	Cross-sectional	23.65 $n = 31$	15	16	Nan	11.6	Central Executive	2-Back, Hit-rate	0.93
Vallat-Azouvi et al., 2007	Severe	Cross-sectional	29.85 $n = 58$	30	28	4.29	11.9	Central Executive	Running Span task, correct	0.8
									Mean effect size	**0.81**

$I^2 = 0$). Mild-moderate TBI demonstrated a lower but moderate effect size, 0.65 ($df = 13$, 95% CIL = 0.53, 0.97, although still homogeneous ($Q = 9.81$, $p < 0.05$, $I^2 = 0$). The smaller variability of each severity level suggests that injury severity is also a moderator affecting WM functioning (see Table 3).

Interactions between injury severity and subcomponents of WM

The fourth stage of the current study was to test the hypothesis that there is an interaction between the two factors: is the deficit in particular WM components affected by the injury severity? All interactions demonstrated homogeneous and significant results (see Figure 3). Central Executive demonstrated the highest effect size for Moderate-Severe TBI of 0.87, ($df = 9$, 95% CIL = 0.41, 1.3) but a moderate effect size for Mild-Moderate TBI of 0.58 ($df = 8$, 95% CIL = 0.55, 0.9). Overall, studies were deemed to be homogeneous (Mild-Moderate- $Q = 6.84$, $p < 0.05$, $I^2 = 0$; Moderate-Severe- $Q = 3.27$, $p < 0.05$, $I^2 = 0$). The Slave system components (i.e., Phonological Loop and Visuo-spatial Sketchpad) both had moderate effect sizes for the different severities; the Phonological Loop component in Mild-Moderate TBI demonstrated a slightly lower effect size of 0.59 ($df = 9$, 95% CIL = 0.59, 0.85) than in Moderate-Severe TBI - 0.66 ($df = 6$, 95% CIL = 0.48, 0.83). Both results were assumed to be homogeneous (Mild-Moderate - $Q = 8.77$, $p<0.05$, $I^2 = 0$; Moderate-Severe- $Q = 6.23$, $p < 0.05$, $I^2 = 3.78$). The Visuo-spatial Sketchpad component showed similar effect sizes on both severity levels; Mild-Moderate TBI demonstrated an effect size of 0.54 ($df = 5$, 95% CIL = 0.54, 0.95) and Moderate-Severe TBI demonstrated 0.51 ($df = 6$, 95% CIL = 0.14, 0.81). Both results were deemed homogeneous (Mild-Moderate -$Q = 8.83$, $p < 0.05$, $I^2 = 43.37$; Moderate-Severe- $Q = 4.18$, $p < 0.05$, $I^2 = 0$). The Episodic Buffer component demonstrated interesting results with a small effect size for Mild-moderate TBI of 0.28, ($df = 1$, 95% CIL = -0.37, 0.98) but moderate effect size for Moderate-Severe TBI of 0.64 ($df = 2$, 95% CIL = 0.01, 1.17). Overall, studies were assumed to be homogeneous (Mild-Moderate- $Q = 0.06$, $p < 0.05$, $I^2 = 0$; Moderate-Severe- $Q = 0.45$, $p < 0.05$, $I^2 = 0$, see 43).

Relationships between WM and EF

First (Figure 4), we found executive functioning was largely affected, demonstrating a high effect size of 0.86 ($df = 12$, 95% CIL = 0.51, 0.83). However, results were not deemed homogeneous, generating a Q value of 15.33, ($p > 0.05$) and $I^2 = 21.72$ which reflects the presence of one or more moderators. Two potential moderators were deemed to be TBI severity and executive functioning domain (fluency vs. flexibility). The interaction between executive functioning and severity revealed similar results: executive functioning demonstrated an effect size for Mild-Moderate TBI of 0.85 ($df = 7$, 95% CIL = 0.41, 0.85) and for Moderate-Severe of 0.88 ($df = 5$, 95% CIL = 0.55, 0.9; $Q = 2.91$, $p < 0.05$, $I^2 = 0$). The executive function in Mild-moderate TBI was not deemed to be homogeneous ($Q = 11.55$, $p > 0.05$, $I^2 = 39.4$), suggesting the presence of the second executive functioning ability moderator. When studies were separated into two meta-analyses reviewing fluency and flexibility domains of executive functioning, a homogeneous effect size was generated for both. As can be seen in Table 5, Mild-Moderate participants were less affected in executive functioning flexibility, with an effect size of 0.6 generated ($Q = 0.43$, $p < 0.05$, $I^2 = 0$, 95% CIL = −0.34, 0.67), less than in executive functioning fluency, with an effect size of 0.94 ($Q = 0.34$, $p < 0.05$, $I^2 = 0$, 95% CIL = 0.4, 1.49). Similarly, Moderate-Severe participants were less affected in executive functioning flexibility, with an effect size of 0.80 generated ($Q = 0.92$, $p < 0.05$, $I^2 = 0$, 95% CIL = 0.40, 1.16) than in executive functioning fluency, with an effect size of 0.96 ($Q = 0.02$, $p < 0.05$, $I^2 = 0$, 95% CIL = 0.37, 1.58). To summarize, performance in the flexibility domain of EF was moderated by injury severity in a similar way than the functioning of the Central Executive of WM, while the fluency domain, which was more severely impaired, did not appear to be moderated by injury severity, contrary to what was found for WM.

Discussion

This meta-analysis and review is the first to examine all of the WM components of Baddeley's' multi-component model (Baddeley, 2020) in adult patients with TBI at varying severities. Surprisingly, very few meta-analyses have been conducted on such "multi" topics. Meta-analyses that have been conducted in the field have either focused on schizophrenia (Forbes et al., 2009), stroke (Lugtmeijer et al., 2020) or pediatric TBI (Phillips et al., 2015), with only three of the components, or examined only one model component on controls (Nee et al., 2013). Furthermore, even empirical or clinical studies including all WM model components at varying TBI severity, were difficult to find. Therefore, we aimed to investigate the effect of varying TBI severities on all components in Baddeley's' "multi-component" model through objective WM outcomes. We were interested in whether WM components were differently affected by the level of TBI severity in adults. We used 24 studies, 21 of which used cross-sectional and three used longitudinal study designs.

The first and most significant finding was that the WM domain as well as all of Baddeley's model components were impaired following TBI, producing a general homogeneous moderate-large to large effect size. Secondly, WM deficit at moderate-severe TBI showed a large effect size compared to a moderate effect size in mild-moderate TBI. These findings provide statistical validation for conclusions of previous qualitative reviews (Azouvi et al., 2017; McAllister et al., 2009; Vakil & Greenstein, 2021; Vakil, 2005).

Of the different model components studied, regardless of severity, Central Executive was found to have the largest impairment generating a large effect size. This was followed by Slave System components of both Phonological Loop and Visuo-spatial Sketchpad with moderate effect sizes, and finally with a slightly smaller effect size, of Episodic Buffer. The results regarding Central Executive and Slave System components are consistent with findings that regardless of injury severity, dysfunction in WM is mainly due to impairment in Central Executive (Phillips et al., 2015). Nevertheless, our review shows that the Central Executive has been more extensively studied than Slave System components. Furthermore, to date there has been little literature examining Episodic Buffer in patients with TBI, adding our findings of moderate Episodic Buffer impairment to the recent consolidating formulation of the WM model with the addition of Episodic Buffer (Baddeley, 2000, 2020).

When studying the interaction between severity and components of WM, we found greater deficit in Central Executive as severity increases (Mild-moderate TBI: large effect size; Moderate-severe TBI: moderate effect size) but similar, moderate effect size, for deficit in Slave System components of Phonological Loop and Visuo-spatial Sketchpad in all severities. Regarding executive functions, the deficit in the flexibility domain was found to be of the same magnitude and to show the same interaction with injury

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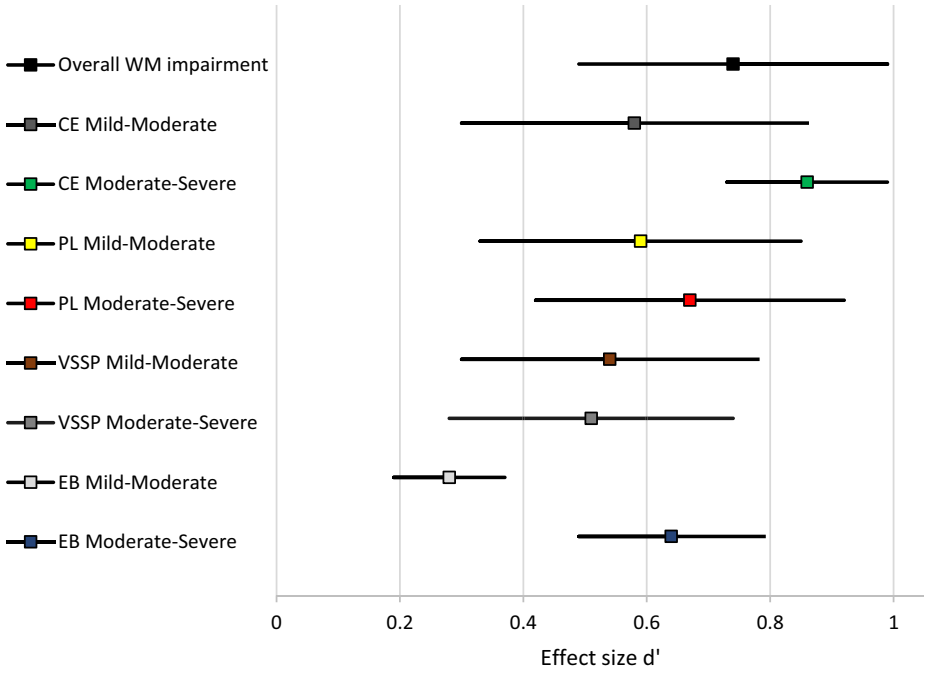

Figure 3. Forest plot showing effect sizes and confidence intervals for the various working memory domains for different injury severity categories.

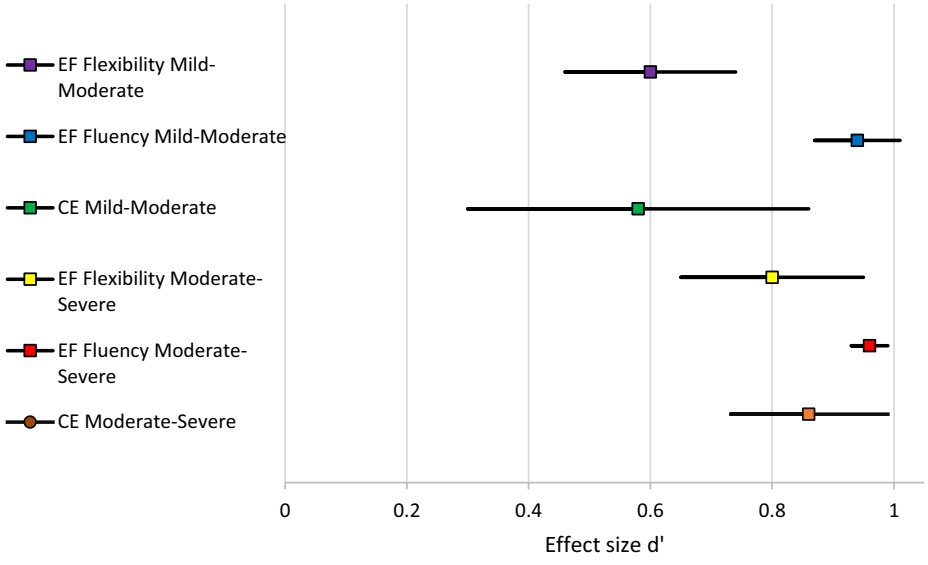

Figure 4. Forest plot showing effect sizes and confidence intervals for central executive working memory, executive functions flexibility and fluency for different injury severity categories.

severity as impairment of the Central Executive of WM. Additionally, Episodic Buffer was found to have a moderate to small effect size for mild-moderate TBI, and a moderate effect size for moderate-severe TBI.

The finding of a moderator effect of injury severity on the Central Executive but not (or to a lesser degree) on the Slave Systems was an interesting result. Indeed, the Central Executive dysfunction might presumably be related to post-traumatic prefrontal dysfunction, which increases with more severe injury. This finding is consistent with previous studies suggesting that WM impairments after TBI are related to an altered activation of a distributed network involving prefrontal structures (Chai et al., 2018; Christodoulou et al., 2001; Sanchez-Carrion et al., 2008). Indeed, the Central Executive has been found to rely heavily on prefrontal structures, particularly the dorsolateral prefrontal cortex (DLPFC) (Jimura et al., 2018; Kim et al., 2015; Murty et al., 2011; Osaka et al., 2003).

In contrast, Slave System functioning has been found to rely more on posterior (parietal) cortex than on prefrontal areas (Andersen & Cui, 2009; Owen et al., 2005), which may explain why Slave System are less affected by TBI severity. The similar moderate effect size for both severity levels is perhaps due to the diffuse nature of the injury, regardless of severity (Graham et al., 2020; Smith & Meaney, 2016).

We hypothesized that dissociation between Central Executive and Slave System impairments at different injury severity levels could be partially explained by greater executive functioning deficits after severe TBI. However, we found a large effect size of

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Table 4. Effect size and methodology of studies sorted by working memory domains and injury severity categories

Author	Working Memory Model component	Injury Severity	Study design	Mean age & participants number	TBI (*n*)	Controls (*n*)	Time since injury (Years)	Education (Years)	Cognitive test	Effect size
Ozen et al., 2013	Central Executive	Mild	Cross-Sectional	20.29 *n* = 34	17	17	5.6	14.76	3-Back, Response time	0.79
Lepach et al., 2015	Central Executive	Mild-Moderate	Cross-Sectional	41.21 *n* = 861	151	710	1.3	10.38	BSCE index of mental control	0.774
Jurick et al., 2018	Central Executive	Mild	Cross-sectional	33.86 *n* = *70*	42	28	6.58	15.04	Digit Span- Backwards, correct	0.54
Jak et al., 2020	Central Executive	Mild	Cross-sectional	33.25 *n* = 44	28	16	7.25	15.37	Combined Z-score of WM index, TMT 1, color-word interference- correct naming	0.49
Konrad et al., 2011	Central Executive	Mild	Cross-sectional	36.85 *n* = 66	33	33	6.02	11.33	Digit Span- Backwards, correct	0.79
Kumar et al., 2013	Central Executive	Mild	Longitudinal	29.25 *n* = 60	30	30	0.17	12.68	Sternberg Paradigm- Verbal d' (False alarm+ Hits)	0.97
Johansson et al., 2009	Central Executive	Mild	Cross-sectional	43.6 *n* = 54	14	40	6.9	16.05	Digit Span- Backwards, correct	0.97
Chen et al., 2012	Central Executive	Mild	Cross-sectional	35.75 *n* = 38	20	18	Nan	15.5	Digit Span- Backwards, correct	0.5
Sanchez-Carrion et al., 2008	Central Executive	Mild	Longitudinal	24.21 *n* = 22	12	10	0.7	11.75	Digit Span- Backwards, correct	0.24
McAllister et al., 2001	Central Executive	Mild	Cross-sectional	29.8 *n* = 30	18	12	Nan	14.45	3-Back, Hit-rate	0.11
									Mean Effect Size	**0.59**
Asloun et al., 2008	Central Executive	Severe	Cross-Sectional	28.6 *n* = 86	43	43	2.6	12.15	2-Back, Hit-rate	0.98
Dores et al., 2017	Central Executive	Severe	Cross-Sectional	28.38 *n* = 19	9	10	3.18	10.50	2-Back, Hit-rate	0.9
Price, 2009	Central Executive	Severe	Cross-Sectional	44.35 *n* = 30	12	18	Nan	Nan	Spatial Span- backwards, correct	0.86
Hanten et al., 2003	Central Executive	Severe	Cross-Sectional	30.1 *n* = 115	70	45	2.7	13.3	SOP (subhect ordered pointing) task, highest level completed	0.99
Coste et al., 2011	Central Executive	Severe	Cross-sectional	27.09 *n* = 66	33	33	0.89	13.86	Running Span, correct	0.87
Coste et al., 2015	Central Executive	Severe	Cross-sectional	27.7 *n* = 30	15	15	3.42	13.4	Visuospatial Span- Backwards, correct	0.77
Draper & Ponsford, 2008	Central Executive	Moderate-Severe	Cross-sectional	42.14 *n* = 104	60	48	31.56	11.78	Digit Span- Backwards, correct	0.55
Johansson et al., 2009	Central Executive	Moderate-Severe	Cross-sectional	42.45 *n* = 52	12	40	11.1	15.1	Digit Span- Backwards, correct	0.98
Palacios et al., 2011	Central Executive	Severe	Cross-sectional	23.65 *n* = 31	15	16	Nan	11.6	2-Back, Hit-rate	0.93
Vallat-Azouvi et al., 2007	Central Executive	Severe	Cross-sectional	29.85 *n* = 58	30	28	4.29	11.9	Running Span task, correct	0.8
									Mean effect size	**0.86**
Ozen et al., 2013	Phonological Loop	Mild	Cross-Sectional	20.29 *n* = 34	17	17	5.6	14.76	Digit Span- Forwards, correct	0.29
Lepach et al., 2015	Phonological Loop	Mild-Moderate	Cross-Sectional	41.21 *n* = 861	151	710	1.3	10.38	Logical Memory 1 (WMS-4)- Immediate memory, correct	0.79
Konrad et al., 2011	Phonological Loop	Mild	Cross-sectional	36.85 *n* = 66	33	33	6.02	11.33	Digit Span- Forwards, correct	0.79
Kwok et al., 2008	Phonological Loop	Mild	Cross-sectional	39.16 *n* = 63	31	32	0.25	10.82	Auditory verbal learning test- Immediate recall, correct	0.51
Kumar et al., 2013	Phonological Loop	Mild	Longitudinal	29.25 *n* = 60	30	30	0.17	12.68	Sternberg Paradigm- Verbal, correct	0.96
Johansson et al., 2009	Phonological Loop	Mild	Cross-sectional	43.6 *n* = 54	14	40	6.9	16.05	Digit Span- Forwards, correct	0.47
Chen et al., 2012	Phonological Loop	Mild	Cross-sectional	35.75 *n* = 38	20	18	Nan	15.5	Digit Span- Forwards, correct	0.2
Sanchez-Carrion et al., 2008	Phonological Loop	Mild	Longitudinal	24.21 *n* = 22	12	10	0.7	11.75	Digit Span- Forwards, correct	0.88
McAllister et al., 2001	Phonological Loop	Mild	Cross-sectional	29.8 *n* = 30	18	12	Nan	14.45	0-Back, correct	0.61
									Mean Effect Size	**0.59**
Asloun et al., 2008	Phonological Loop	Severe	Cross-Sectional	28.6 *n* = 86	43	43	2.6	12.15	Dual Task 1-Back, Hit-rate	0.99
Zimmermann et al., 2017	Phonological Loop	Moderate-Severe	Cross-Sectional	36.2 *n* = *65*	26	39	1.9	9.5	Auditory word span, correct	0.42
Coste et al., 2015	Phonological Loop	Severe	Cross-sectional	27.7 *n* = 30	15	15	3.42	13.4	Digit Span- Forwards, correct	0.7
Draper & Ponsford, 2008	Phonological Loop	Moderate-Severe	Cross-sectional	42.14 *n* = 104	60	48	31.56	11.78	Digit Span- Forwards, correct	0.39
Johansson et al., 2009	Phonological Loop	Moderate-Severe	Cross-sectional	42.45 *n* = 52	12	40	11.1	15.1	Digit Span- Forwards, correct	0.95
Palacios et al., 2011	Phonological Loop	Severe	Cross-sectional	23.65 *n* = 31	15	16	Nan	11.6	Digit Span- Forwards, correct	0.47
Vallat-Azouvi et al., 2007	Phonological Loop	Severe	Cross-sectional	29.85 *n* = 58	30	28	4.29	11.9	Letter span- Forwards, correct	0.72

(*Continued*)

Table 4. (*Continued*)

Author	Working Memory Model component	Injury Severity	Study design	Mean age & participants number	TBI (*n*)	Controls (*n*)	Time since injury (Years)	Education (Years)	Cognitive test	Effect size
									Mean effect size	**0.67**
Ozen et al., 2013	Visuospatial Sketchpad	Mild	Cross-Sectional	20.29 $n = 34$	17	17	5.6	14.76	Digit-Symbol (WAIS-4), correct	0.45
Lepach et al., 2015	Visuospatial Sketchpad	Mild-Moderate	Cross-Sectional	41.21 $n = 861$	151	710	1.3	10.38	Visual WM index (WMS-4)	0.83
Konrad et al., 2011	Visuospatial Sketchpad	Mild	Cross-sectional	36.85 $n = 66$	33	33	6.02	11.33	Trail Making-1, time	0.79
Kumar et al., 2013	Visuospatial Sketchpad	Mild	Longitudinal	29.25 $n = 60$	30	30	0.17	12.68	Sternberg Paradigm- Visual, correct	0.29
Johansson et al., 2009	Visuospatial Sketchpad	Mild	Cross-sectional	43.6 $n = 54$	14	40	6.9	16.05	Block Span- Forwards, correct	0.58
									Mean Effect Size	**0.54**
Zimmermann et al., 2017	Visuospatial Sketchpad	Moderate-Severe	Cross-Sectional	36.2 $n = 65$	26	39	1.9	9.5	Trail Making-1, time	0.27
Price, 2009	Visuospatial Sketchpad	Severe	Cross-Sectional	44.35 $n = 30$	12	18	Nan	Nan	Spatial Span- backwards, correct	0.78
Spikman et al., 2012	Visuospatial Sketchpad	Moderate-Severe	Cross-Sectional	30.05 $n = 73$	28	55	Nan	12	Trail Making-1, time	0.77
Coste et al., 2015	Visuospatial Sketchpad	Severe	Cross-sectional	27.7 $n = 30$	15	15	3.42	13.4	Visuospatial Span- Forwards, correct	0.63
Draper & Ponsford, 2008	Visuospatial Sketchpad	Moderate-Severe	Cross-sectional	42.14 $n = 104$	60	48	31.56	11.78	Digit-Symbol (WAIS-4), correct	0.37
Johansson et al., 2009	Visuospatial Sketchpad	Moderate-Severe	Cross-sectional	42.45 $n = 52$	12	40	11.1	15.1	Block Span- Forwards, correct	0.2
Vallat-Azouvi et al., 2007	Visuospatial Sketchpad	Severe	Cross-sectional	29.85 $n = 58$	30	28	4.29	11.9	Block Span- Forwards, correct	0.54
									Mean effect size	**0.51**
Belleville et al., 2006	Episodic Buffer	Mild	Cross-sectional	64.11 $n = 45$	28	17	Nan	14.6	Face-name association task, correct	0.35
Monti et al., 2013	Episodic Buffer	Mild	Cross-sectional	22.35 $n = 24$	12	12	4	15.5	Face-name association task, correct	0.21
									Mean Effect Size	**0.28**
Price, 2009	Episodic Buffer	Severe	Cross-Sectional	44.35 $n = 30$	12	18	Nan	Nan	Object Span- COAD (computerized object and abstract designs test)	0.77
Coste et al., 2011	Episodic Buffer	Severe	Cross-sectional	27.09 $n = 66$	33	33	0.89	13.86	Short-term binding task (STB), correct maintenance score	0.48
Coste et al., 2015	Episodic Buffer	Severe	Cross-sectional	27.7 $n = 30$	15	15	3.42	13.4	Short-term binding task (STB), correct maintenance score	0.66
									Mean Effect Size	**0.64**

Table 5. Effect size and methodology of studies sorted by executive function fluency and executive function flexibility memory domains

Author	Executive Function domain	Injury Severity	Study design	Mean age & participants number	TBI (*n*)	Controls (*n*)	Time since injury (Years)	Education (Years)	Cognitive test	Effect size
Lepach et al., 2015	Flexibility	Mild-Moderate	Cross-Sectional	41.21 *n* = 861	151	710	1.3	10.38	BSCE index of inhibition	0.50
Jak et al., 2020	Flexibility	Mild	Cross-Sectional	33.25 *n* = 44	28	16	7.25	15.37	Combined Z score of WCST, TMT-2, Stroop inhibition	0.71
									Mean Effect size	**0.61**
Spikman et al., 2012	Flexibility	Moderate-Severe	Cross-Sectional	30.05 *n* = 73	28	55	Nan	12	Six element test (SET)	0.95
Coste et al., 2011	Flexibility	Severe	Cross-sectional	27.09 *n* = 66	33	33	0.89	13.86	Plus Minus Task, completion time	0.80
Draper & Ponsford, 2008	Flexibility	Moderate-Severe	Cross-sectional	42.14 *n* = 104	60	48	31.56	11.78	Hayling Brixton test, total errors	0.64
									Mean Effects Size	**0.79**
Zimmermann et al., 2017	Fluency	Moderate-Severe	Cross-Sectional	36.2 *n* = 65	26	39	1.9	9.5	Phonetic fluency, correct	0.97
Konrad et al., 2011	Fluency	Mild	Cross-sectional	36.85 *n* = 66	33	33	6.02	11.33	Semantic fluency, correct	0.81
Kwok et al., 2008	Fluency	Mild	Cross-sectional	39.16 *n* = 63	31	32	0.25	10.82	Semantic fluency, correct	0.98
Kumar et al., 2013	Fluency	Mild	Longitudinal	29.25 *n* = 60	30	30	0.17	12.68	Total fluency score, correct	0.98
Johansson et al., 2009	Fluency	Moderate-Severe	Cross-sectional	42.45 *n* = 52	12	40	11.1	15.1	Total fluency score, correct	0.99
McAllister et al., 2001	Fluency	Mild	Cross-sectional	29.8 *n* = 30	18	12	Nan	14.45	Total fluency score, correct	0.88
									Mean Effect Size	**0.94**
Zimmermann et al., 2017	Fluency	Moderate-Severe	Cross-Sectional	36.2 *n* = 65	26	39	1.9	9.5	Phonetic fluency, correct	0.97
Coste et al., 2011	Fluency	Cross-sectional	27.09 *n* = 66	33	33	0.89	13.86	Severe	Phonetic fluency, correct	0.94
Johansson et al., 2009	Fluency	Moderate-Severe	Cross-sectional	42.45 *n* = 52	12	40	11.1	15.1	Total fluency score, correct	0.99
									Mean Effect Size	**0.96**

global executive functioning deficits in both severities. After a careful examination of the heterogeneity found in executive functioning measures, we identified a moderator effect of executive functioning tasks, reflecting that different tasks measure different domains of executive functioning. As this is consistent with the fractioning models of EF, to inhibition, interference control, cognitive flexibility (Diamond, 2013) or updating, inhibition and shifting (Miyake et al., 2000), we ran separate meta-analyses for verbal fluency tasks and flexibility/shifting tasks. We have done this on the basis of studies showing verbal fluency as a separate executive function common factor modulating more global efficiency and affected differently than other components of EF (Gustavson et al., 2020). This might be due to language processing involvement as a crucial component of this task (Whiteside et al., 2016).

Tasks measuring flexibility / shifting showed a similar interaction with injury severity as Central Executive tasks, suggesting that the Central Executive and flexibility are two cognitive domains that exhibit a biological gradient with TBI; they are more impaired on average as TBI severity increases. This pattern was not found for the executive functioning fluency tasks, yielding a large effect size for both severities. The possible overlapping prefrontal activation of Central Executive and shifting EF, both requiring the integration and manipulation of information, might offer a possible explanation for EF and Central Executive effect size similarity (Chai et al., 2018; Uddin, 2021).

An additional finding is a small effect size for Episodic Buffer in mild-moderate TBI, as opposed to a moderate effect size for moderate-severe TBI. This result suggests that the Episodic Buffer relies both on Slave System and Central Executive components, with greater involvement of Central Executive and smaller (but still present) involvement of Slave System. Due to possible measurement confounding (Dunning et al., 2016; de Pontes Nobre et al., 2013), there is less literature about Episodic Buffer in patients with TBI. However, dual-modality tasks for measuring Episodic Buffer appear to support the Episodic Buffer model component as linking between the Central Executive and slave systems (Baddeley et al., 2018; Baddeley, 2000). Possibly, the dissociation of Episodic Buffer dysfunction at different severity levels might be explained by the mutual reliance of Episodic Buffer, Central Executive and flexibility in EF in the engagement of strategy selection (Collette & Van Der Linden, 2002).

Studying a WM component through different TBI severities, may shed new theoretical light on the WM structure. First, regarding the findings of dissociation for the similar effect size on Slave Systems at both severity levels, but larger effect size in executive functioning of flexibility for severe TBI : this suggests that brain injury at all severity levels affects a wide range of cognitive functions, reducing general cognitive capacity (reflected by the impairment of both Slave Systems and Central Executive) (Azouvi et al., 2017; Vallat-Azouvi et al., 2007). However, in the more severe TBI cases, the unique frontal lobe profile is largely expressed as affecting Central Executive more clearly (Kavé & Heinik, 2017; Larson et al., 2012). However, the current results do not reveal what is behind that primary capacity reduction regardless of severity. Future research might answer that question.

Secondly, we find that the dissociation between severities in Episodic Buffer as well support the Episodic Buffer as a multi-link component, linking Slave System, Central Executive, long-term memory, and EF. Expanding Baddeley's' link between Central Executive and long-term memory (Baddeley, 2017), our current finding of the larger, moderate, effect size of Episodic Buffer in

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moderate-severe TBI, might explain its role in common dysfunctions after moderate-severe TBI of long-term memory and Central Executive (Azouvi et al., 2017; Cappa et al., 2011; Vallat-Azouvi et al., 2007). Nevertheless, we cannot exclude the possibility of a link between Episodic Buffer and Slave Systems, but those links need further investigation.

Our results might also suggest some clinical implications, indicating a variety of WM deficit 'profiles' in all TBI severities. At the group level, the present results suggest that, on average, individuals with TBI, particularly after severe TBI, suffer from severe deficits of the Central Executive, while slave systems are less severely impaired. However, the profile of impairment was found to be different across different injury severity levels. In addition, we cannot exclude that the profile of impairments across the WM components may vary from one individual to the other, depending on the underlying brain lesions. These findings should encourage clinicians to assess specifically each WM component in a given patient, in order to adapt interventions more precisely to each individual's impairments, rather than addressing only one global measure of WM for assessment or treatment.

We need to acknowledge several limitations in the present study. Given the small number of studies that conformed to our strict inclusion criteria, we did not separate studies according to age, gender, or time since injury. These potential moderators should be evaluated in future studies, especially time since injury and age at injury which are known to affect WM functioning (Azouvi et al., 2017; Dunning et al., 2016) and could not be analyzed in our study due to insufficient data. In addition, it should be acknowledged that the included studies defined severity of TBI using various markers which do not always align, such as GCS, duration of LOC or duration of PTA. This may have impacted on the accuracy of the results. Additional important factors to mention, that may cause possible bias, and were not assessed in our study due to insufficient data: blind assessment and method of recruitment; it is impossible to know whether patients have more or less initial complaints of WM deficits, introducing a bias of recruitment affecting the results. Future studies examining WM structure should be theoretically based, examining four components of WM under several clinical populations. Comparisons of different deficit profiles (i.e., focal injury in vascular disease or diffuse axonal injury in multiple sclerosis) besides varying severities, could expand our understanding of the relations between the model's components.

Despite these limitations, it is essential to conduct this meta-analysis and to examine the functioning of WM in TBI patients.

Conclusion

Despite the limitations presented, the outcomes of the present meta-analysis and review revealed important trends regarding WM structure and relations between Baddeley's four components model, allowing for a better understanding of WM deficits in varying severities of TBI. The theoretical and clinical implications of these deficits are not yet well understood; however, findings suggest WM should first be assessed and then treated in all routine clinical practice and when developing plans for interventions (Hellgren et al., 2015; Vallat et al., 2010; Vallat-Azouvi et al., 2009, 2014). Future research should focus on studies with strict inclusion criteria for known moderating factors, including wider heterogeneity of pathologies and WM deficit profile. This will result in further revelations about general WM structure and specific WM deficits in individuals with TBI.

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