Working Memory Capacity and Influencing Factors: Evidence from Meta-Analysis

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Abstract

Working memory capacity, as a fundamental psychological function of individuals, is influenced by multiple factors in its specific manifestations. This study employed meta-analytic methods to examine individual working memory capacity and its influencing factors. Through systematic searches of multiple databases, 100 scholarly articles related to working memory capacity from domestic and international sources between 2000–2024 were ultimately collected, with a total sample size of 29,014. CMA3.3.7 and R4.4.1 were used to conduct main effect analysis and moderating effect tests. The results indicated that: (1) the MEAN effect size for individual working memory capacity was 0.780 ($P < 0.001$); (2) cognitive load, subsystem, physical and mental state, and age were moderating variables, while cultural background was not a moderating variable.

Full Text

Working Memory Capacity and Its Influencing Factors: Evidence from a Meta-Analysis

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Abstract

Working memory capacity represents a fundamental psychological function, and its performance is influenced by numerous factors. This study employed meta-analytic methodology to investigate individual working memory capacity and its influencing factors. Through systematic searches of multiple databases, we collected 100 professional publications on working memory capacity from domestic and international sources spanning 2000–2024, with a total sample size of 29,014. Main effects and moderating effects were analyzed using CMA 3.3.7 and R 4.4.1 software. The results demonstrated that: (1) the MEAN effect size for individual working memory capacity was 0.780 ($P < 0.001$); (2) cognitive load, subsystem, physical and mental state, and age served as significant moderating variables, whereas cultural background did not.

Keywords: working memory capacity, working memory theory, meta-analysis, moderating effect

Introduction

Working memory refers to the process by which individuals retrieve necessary information from memory systems that is currently active during cognitive operations (Baddeley, 2012). The working memory system comprises the central executive system, visuospatial sketchpad, phonological loop, and episodic buffer. Researchers have proposed that the working memory system possesses a capacity threshold for controlling relevant information during cognitive activities—information within this threshold can be effectively processed, while information beyond it cannot enter the cognitive processing stream. Consequently, the proportion of total information that can be correctly processed in a given task represents an individual' s working memory capacity (Olivers & Meeter, 2008). Given that working memory capacity constitutes a complex psychological function with multifaceted components and manifestations, scholars have conducted extensive research to clarify its nature and influencing factors.

2.1 Effects of Cognitive Load on Working Memory Capacity

Research indicates that cognitive load levels significantly affect working memory capacity (Ninomiya et al., 2024). In low cognitive load conditions ($N = 0$ or 1) of the N-back paradigm, individuals demonstrate high working memory capacity, typically retaining over 95% of relevant information (Li et al., 2022; Gallant et al., 2020). However, this elevated capacity under low load may reflect a ceiling effect, as stimuli are presented at approximately 300ms intervals, enabling nearly instantaneous retrieval of working memory information and potentially inflating capacity estimates (Dede et al., 2014). To avoid ceiling effects, researchers typically employ higher cognitive load levels ($N \geq 2$). Studies using 2-back paradigms report working memory capacity ranging from 0.78 to 0.88 (Lejbak et al., 2011; Chen et al., 2023), while 3-back paradigms generally yield lower capacity than 2-back conditions (Blanchard et al., 2011; Guo et al., 2012), though some research finds no significant difference between them (Kong et al., 2023). Limited studies using 4-back paradigms show further capacity reductions (Mashal & Metzuyanim-Gorelick, 2019), though excessively high cognitive load may produce floor effects that compromise results (Frederick, 2000). Consequently, N-values exceeding 3 typically serve only as relative reference points.

Nevertheless, existing evidence demonstrates a clear declining trend in working memory capacity as cognitive load increases in N-back paradigms.

2.2 Effects of Working Memory Subsystems on Working Memory Capacity

According to Baddeley (2012), individuals utilize the visuospatial sketchpad and phonological loop to process visuospatial and phonological information respectively, with each subsystem exhibiting distinct capacity characteristics. Research indicates that visuospatial sketchpad capacity typically ranges from 0.45 to 0.88 (Wu et al., 2024; Li et al., 2019), whereas phonological loop capacity ranges from 0.51 to 0.95 (Wu et al., 2024; Lin et al., 2020). Overall, the visuospatial sketchpad demonstrates lower capacity limits than the phonological loop, suggesting inferior capacity. Additionally, researchers employing dual-task paradigms to examine integrated working memory system functioning have found that dual-task conditions produce lower capacity than single-task conditions, indicating that simultaneous activation of both subsystems leads to more pronounced capacity reductions (Israel et al., 2015; Jaeggi et al., 2010). These findings collectively demonstrate that using different subsystems yields differential working memory capacity, with concurrent processing across both subsystems producing more substantial capacity changes.

2.3 Effects of Physical and Mental State on Working Memory Capacity

Research demonstrates that working memory capacity is significantly influenced by individuals' physical and mental states (Passareli-Carrazzoni et al., 2018). Studies comparing ADHD individuals with controls reveal lower capacity in ADHD groups—0.74 versus 0.91 in 2-back paradigms, and 0.65 versus 0.70 in 3-back paradigms (Chantiluke et al., 2015). Scholars contend that deviations from normal psychological thresholds impair working memory capacity (Williams et al., 2022). Comparative studies of ASD individuals show mixed results: lower capacity in 2-back paradigms (Yuk et al., 2020) but comparable or slightly higher capacity in 3-back conditions (Chantiluke et al., 2015). While most research confirms that abnormal psychological states reduce working memory capacity relative to normal states, occasional contradictory findings emerge. Studies examining individuals with chronic illnesses or post-prognosis conditions also report reduced capacity compared to healthy controls (Mercado et al., 2022; Luxton et al., 2014). In summary, both psychological and physical abnormalities produce significant differences in working memory capacity, typically showing reduced capacity in abnormal populations, though isolated studies report opposite patterns.

2.4 Effects of Age on Working Memory Capacity

Researchers posit that working memory capacity is not static but changes with age, as psychological functions depend on physiological foundations that themselves undergo developmental changes (Jeneson & Squire, 2011). Studies report elderly individuals' capacity as 0.71 in 2-back paradigms, compared to 0.96 for young adults and 0.86 for middle-aged adults (Schott & Krull, 2019; Pergher et al., 2021; Mercado et al., 2022). This decline likely reflects age-related brain deterioration affecting the physiological basis of working memory systems (Lee et al., 2023). Young and middle-aged adults represent peak physiological and psychological functioning, potentially yielding maximal capacity (Heled et al., 2022). For minors, capacity ranges from 0.51 to 0.98 (Pelegrina et al., 2015; Yanai & Maekawa, 2011), substantially lower than young adults and similar to elderly performance, possibly due to immature physiological and psychological functions (Bucaille et al., 2022). Overall, age-related working memory capacity follows an inverted U-shaped trajectory, peaking during young and middle adulthood while declining in elderly and minor populations. However, research has not definitively established whether elderly capacity exceeds that of minors, nor whether young adults outperform middle-aged adults.

2.5 Effects of Cultural Background on Working Memory Capacity

Cultural backgrounds can be broadly categorized as Eastern or Western (McFarland & Wehbe-Alamah, 2019). While numerous studies demonstrate significant cultural differences in values and decision-making (Güler et al., 2023), research on cultural influences on basic psychological functions remains limited. Working memory studies typically employ convenience sampling, recruiting participants from local populations that carry cultural characteristics, potentially influencing capacity. Eastern cultural background participants show capacity ranging from 0.88 to 0.93 (Guo et al., 2023; Zhang et al., 2021), while Western participants range from 0.82 to 0.92 (Lamichhane et al., 2020; Gajewski et al., 2018). The overlapping ranges suggest potential differences requiring further analysis.

Collectively, decades of working memory capacity research have examined numerous influencing factors, yielding both convergent findings and contradictory results. Some topics remain controversial, while others await systematic investigation. To reconcile these discrepancies and explore potential research directions, we propose the following hypotheses based on existing literature: (1) cognitive load level differences do not significantly affect working memory capacity; (2) subsystem processing characteristic differences do not significantly affect capacity; (3) physical/mental state differences do not significantly affect capacity; (4) age differences do not significantly affect capacity; (5) cultural background differences do not significantly affect capacity.

3.1 Literature Search and Screening

We systematically searched Chinese and international databases including CNKI, Superstar Digital Library, Wanfang Data, VIP Information, National Library of China, Duxiu Academic Search, Google Scholar, Web of Science, Science Direct, PubMed Central, ResearchGate, Springer Link, and Sage for literature from 2000–2024. Search terms included: memory, working memory, working memory capacity, working memory theory, Baddeley, N-back, and corresponding Chinese translations. Inclusion criteria were: (1) quantitative behavioral studies using N-back paradigms; (2) explicit reporting of N-values (2 or 3), experimental procedures, stimulus materials (symbols, locations, or images), and single versus dual-task paradigms; (3) explicit reporting of participant numbers and demographic variables; (4) explicit reporting of effect sizes; (5) availability of complete full-text in Chinese or English. This search yielded 2,923 publications, from which we extracted 160 independent effect sizes for 2-back, 53 for 3-back, 55 for visuospatial sketchpad, 152 for phonological loop, 6 for dual-system, 134 for Eastern cultural background, and 79 for Western cultural background. The screening process is illustrated in [Figure 1: see original paper].

3.2 Variable Coding

We coded study characteristics including N-back paradigm (N = 2 or 3 representing cognitive load), subsystems (phonological loop, visuospatial sketchpad, dual-system), and cultural background (Eastern vs. Western). Effect sizes were coded per independent sample, with multiple studies within a single publication coded separately. Studies reporting participant numbers, means, and variance/standard deviation were comprehensively coded. To ensure accuracy, we performed test-retest coding on 20% of data after two weeks, revealing no discrepancies.

3.3 Data Processing

Analyses employed CMA 3.3.7 and R 4.4.1. To address varying metrics across studies, we standardized all working memory capacity and variance/standard deviation values to decimal form. Studies reporting correct response counts were converted using total trial numbers. For pre-post designs, we synthesized means and variances/standard deviations using the following formulas:

$$\bar{X}_T = \frac{\sum N_{iX}i}{\sum N_i}, \quad \bar{S}_T = \sqrt{\frac{\sum N_{iS}i^2 + \sum N_{id}i}{\sum N_i}}, \quad d_i = \bar{X}_T - \bar{X}_i$$

where $\bar{X}_T$ represents the total mean, X_i group means, N_i group sizes, S_i group standard deviations, and $\bar{S}_T$ the pooled standard deviation (Zhang & Xu, 2004, p. 90). We used the arithmetic mean (MEAN) effect size as our working memory capacity indicator due to its broad applicability and straightforward interpretability (Sardanelli et al., 2019). Heterogeneity was assessed using Q-tests, with fixed-effects models applied under homogeneity and random-effects models under heterogeneity. Publication bias was evaluated via funnel plots, fail-safe N, Begg' s test, and Egger' s test.

4.1 Heterogeneity Test

Heterogeneity analysis revealed significant Q-values for MEAN effect sizes ($P < 0.001$), indicating substantial heterogeneity across studies. The I^2 value of 99.782% indicated that observed variation primarily reflected true effect size differences rather than random error, representing high heterogeneity ($I^2 >$ 75%; Luo & Leng, 2013, pp. 121-122). Consequently, we employed random-effects models.

4.2 Main Effect Test

Analysis of 213 MEAN effect sizes yielded a main effect of 0.780, with a 95% confidence interval not crossing zero, indicating significant working memory capacity (see).

4.3 Moderating Effect Test

Significant Q-values suggested the presence of moderating variables. Analysis of cognitive load, subsystem, physical/mental state, age, and cultural background revealed significant effects for four moderators. Effect size ordering was: 2-back > 3-back for cognitive load; phonological loop > visuospatial sketchpad > dual-system for subsystems; normal > abnormal for physical/mental state; and young > middle-aged > elderly > minor for age. Cultural background showed no significant moderating effect (see).

4.4 Publication Bias Analysis

Visual inspection of the funnel plot ([Figure 2: see original paper]) showed most studies clustered at the top with minimal dispersion, suggesting low publication bias. The fail-safe N exceeded Rosenthal' s criterion of 5k + 10 (where k = number of studies), requiring 19,772 null studies to overturn our findings (Viechtbauer, 2007). Begg' s test ($df = 212$, $Z = 1.140$, $P = 0.254 > 0.05$) and Egger' s test ($df = 212$, $Z = -1.228$, $P = 0.220 > 0.05$) confirmed absence of publication bias. These indicators demonstrate robust, unbiased results.

5.1 Working Memory Capacity

Working memory capacity has long concerned researchers, who have employed diverse methods to examine its nature and influencing factors (Thomason et al., 2009). Previous studies typically investigated capacity under fixed cognitive loads (e.g., 2-back or 3-back paradigms; Lee et al., 2022; Turtola & Covey, 2021), yielding heterogeneous results. Few studies have integrated findings across different load levels. Our meta-analysis addresses this gap by synthesizing results to derive a meaningful effect size. The main effect of 0.780 indicates that individuals can temporarily maintain 78% of relevant information when using working memory systems, representing a stable capacity estimate across two decades of research. The high I^2 value indicates substantial heterogeneity, necessitating moderating effect analyses to identify influencing factors.

5.2.1 Moderating Effect of Cognitive Load

Cognitive load significantly impacts working memory capacity, with capacity decreasing as load increases (Gao et al., 2024). Our findings demonstrate significantly higher capacity in 2-back versus 3-back conditions, consistent with prior research showing capacity attenuation under increased load. Resource limitation theory posits that information processing consumes cognitive resources throughout the entire process, including resources allocated to counteract interfering factors (Kahneman, 1970, 1973, pp. 148-152). Since total cognitive resources are limited, heightened interference can divert resources from primary processing, reducing efficiency. Increased cognitive load amplifies these interfering factors (Kuriakose et al., 2024; Ploetzner, 2024), requiring greater resource allocation for interference suppression and leaving insufficient resources for information processing. This resource insufficiency reduces working memory system efficiency, manifested as decreased capacity that becomes more pronounced with higher cognitive loads.

5.2.2 Moderating Effect of Subsystems

When processing different material attributes, corresponding subsystems activate. Complex materials may simultaneously activate both phonological loop and visuospatial sketchpad (Belletier et al., 2021). Research confirms differential capacity across subsystems (Singh & Yathiraj, 2024), with our moderation analysis establishing the significance of these differences. Phonological loop capacity significantly exceeds visuospatial sketchpad capacity, likely because all processed information ultimately undergoes semantic encoding in the brain (Murray et al., 2017). The phonological loop specializes in processing linguistic information (digits, letters, words, sounds) that forms the basis of semantic encoding, enabling low-loss, high-efficiency conversion and freeing resources for capacity itself (Baddeley, 1998). In contrast, the visuospatial sketchpad processes pictures and locations that differ substantially from brain' s default encoding format (Duff & Logie, 1999), requiring resource-consuming conversion to semantic codes (Zhai et al., 2022) and reducing available capacity resources. The lowest capacity (approximately 55.1%) occurs during dual-system activation, as concurrent resource consumption by both systems inevitably leaves at least one subsystem resource-deprived (Katus & Eimer, 2019), impairing collaborative processing and reducing overall capacity.

5.2.3 Moderating Effect of Physical and Mental State

Physical and mental states are dialectically unified, with psychological functions requiring physiological foundations that can be reciprocally modified (Packheiser et al., 2024; Lawton et al., 2017). This integrated perspective suggests that working memory capacity, as a fundamental psychological function, reflects overall physical and mental state. Our moderation analysis reveals significantly higher capacity in normal versus abnormal states. Abnormal states disrupt working memory system functioning, impairing both subsystems and central executive processes (Fan et al., 2024). Neuroimaging research demonstrates structural brain differences in psychopathological populations (González-Alemañy et al., 2023), altering the physiological basis of central executive and subsystem operations and producing differential processing efficiency (Huang et al., 2025). Consequently, normal populations exhibit superior working memory capacity.

5.2.4 Moderating Effect of Age

Age serves as a marker for developmental stages (Kaskie & Lepore, 2024). Our moderation analysis reveals significant capacity differences across minors, young adults, middle-aged adults, and elderly individuals, following the pattern: young > middle-aged > elderly > minor. Young adults' superior capacity aligns with expectations, as peak physiological functioning combines with mature psychological processing for maximal efficiency (Shahin et al., 2023). Middle-aged adults maintain relatively high capacity despite modest physiological decline by leveraging extensive processing experience and established schemas (Klaassen et al., 2014). Elderly adults' lower capacity reflects both physiological deterioration and potential rigidity from entrenched schemas (Poole et al., 2022), which may impair working memory efficiency. Surprisingly, minors show the lowest capacity despite good physiological condition, likely due to immature psychological functions and limited processing experience (Mayer, 2019). Their working memory systems may simultaneously process information and acquire new schemas, consuming resources and reducing efficiency.

5.2.5 Moderating Effect of Cultural Background

Global culture comprises primarily Western (Anglo-Saxon) and Eastern (Chinese) cultural spheres, with others representing extensions (Bisin & Verdier, 2001; Kinzig et al., 2004). While cultural background influences psychological functions (Stigler et al., 1990) and behavioral patterns (Güler et al., 2023), our moderation analysis found no significant effect on working memory capacity. This may reflect the working memory system' s fundamental role in abstract, high-level encoding and storage of culturally marked information (Cowan et al., 2014). The null finding suggests cross-cultural consistency in this basic psychological function, indicating that despite surface-level behavioral and conceptual differences, Eastern and Western populations share similar underlying working memory structures and encoding mechanisms. This demonstrates greater commonality than individuality in working memory capacity across human populations.

Working memory capacity is influenced by multiple factors (Nugroho et al., 2023). Our moderation analyses confirm significant effects for several factors while identifying future research directions. Regarding cognitive load, our findings establish differences at moderate-high levels (N = 2, 3), but ceiling effects at low loads (N = 0, 1) preclude robust conclusions (Dede et al., 2014), necessitating methodological innovations to characterize low-load capacity. Current research emphasizes phonological loop and visuospatial sketchpad capacity, with our analysis confirming significant differences, yet the episodic buffer remains understudied and warrants greater attention. Real-world working memory usage involves integrated, multi-subsystem processing, suggesting need for more ecologically valid dual-task research. Physical and mental abnormalities significantly reduce capacity, potentially explaining suboptimal treatment outcomes in clinical populations whose impaired systems cannot fully process therapeutic information—future research should develop interventions that minimize these negative effects. Age-related findings showing minors'lower capacity than elderly individuals suggest that accumulated experience and schemas may outweigh raw physiological function, highlighting the importance of enriching minors' experiences and developing effective training to internalize schemas. Finally, the null cultural background effect suggests researchers need not constrain sampling by culture, enhancing generalizability.

Conclusion

This meta-analysis yields a MEAN effect size of 0.780 for working memory capacity, significantly moderated by several variables. Capacity ordering was: 2-back > 3-back for cognitive load; phonological loop > visuospatial sketchpad > dual-system for subsystems; normal > abnormal for physical/mental state; and young > middle-aged > elderly > minor for age. Cultural background showed no significant moderating effect, indicating equivalent capacity across cultures.

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Note: Figure translations are in progress. See original paper for figures.