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REVIEW

Effects of acute alcohol administration on working memory: a systematic review and meta-analysis

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Abstract

Rationale Alcohol-induced executive function deficits may underlie associations between alcohol, self-regulation, and hazardous behaviors. Studies examining the effects of alcohol administration on working memory, an important executive functioning component, have produced mixed findings. Acute alcohol effects on working memory remain unclear.

Objectives We aimed to conduct a systematic review and meta-analysis on the effects of acute alcohol administration on working memory outcomes in studies of healthy adults.

Methods We performed a systematic search of PubMed, MEDLINE, and PsycINFO from inception to June 2021. Studies were included if they met criteria, including healthy participants and administration of quantified alcohol doses against comparative controls. Data extracted included primary working memory outcomes, alcohol doses, and study characteristics. Study quality was assessed using an established validity measure. Working memory task type, alcohol dose, control condition type, and sex/gender composition were explored as moderators using mixed-effects models and meta-regressions.

Results Thirty-two studies (1629 participants) provided sufficient data for 54 comparisons between alcohol and control conditions. Random-effects meta-analysis indicated that alcohol administration produced significant, small- to medium-sized working memory decrements (g [95% CI] = −0.300 [−0.390 to −0.211], $p < 0.001$). Moderation analyses suggested that these effects differed as a function of task type, dose, control condition type, and sex/gender composition. The average quality rating across studies was good.

Conclusions Alcohol administration significantly impaired working memory performance, particularly when executive-related manipulation processes were involved. Future research is needed to investigate how alcohol-induced working memory impairments relate to compromised self-regulation, hazardous behavior, and negative drinking consequences.

Keywords Alcohol · Administration · Working memory · Meta-analysis · Systematic review

Introduction

Several models have implicated alcohol-induced executive function impairments in problematic alcohol use and related consequences (Giancola 2000; Giancola et al. 2010; Lyvers 2000; Steele and Josephs 1990). Executive functions are multifaceted higher-order cognitive processes that govern self-regulation and goal-directed behaviors (Lezak et al. 2012; Lieberman 2007; Luria 1966; 1969; Suchy 2009). Impairments in executive functioning can play a large role in the failure to self-regulate behavior (Baumeister and Heatherton 1996; Heatherton and Wagner 2011). Alcohol consumption has been associated with executive function decrements (Abernathy et al. 2010; Day et al. 2015; Ralevski et al. 2012) and hazardous behaviors related to self-regulation, such as risk-taking (Cronce and Corbin 2010; Maisto et al.

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2002, 2004; Scott et al. 1999; Smith et al. 1999). Several models have implicated alcohol-induced executive function impairments in problematic alcohol use and related consequences (Giancola 2000; Giancola et al. 2010; Lyvers 2000; Steele and Josephs 1990). Therefore, alcohol's acute effects on executive functions may interfere with control over drinking behaviors, leading to problematic use and negative consequences (Field et al. 2010; Fillmore et al. 2006; Leeman et al. 2012; Noël et al. 2011).

As a critical component of executive functioning, working memory may be a particularly important factor in the nexus of problematic alcohol use, executive functioning, and self-regulation (Abernathy et al. 2010; Day et al. 2015; Mintzer 2007). Working memory allocates attention toward encoding, integrating, updating, and manipulating information quickly to achieve goals (Cowan 2010; Goldstein 2008; Miyake and Shah 1999). As such, working memory plays a primary role in weighing consequences, maintaining task-related goals, and integrating multiple information sources to engage in goal-directed behaviors (Baddeley and Hitch 1974; Miyake and Shah 1999). These features are likely important for navigating dynamic situations involving alcohol consumption. Alcohol-induced working memory impairments may compromise goals for controlling drinking behaviors (e.g., intended drinking limits) and avoiding risks associated with hazardous use (Lechner et al. 2016). For these reasons, clinical researchers have been increasingly interested in explicating the acute effects of alcohol on working memory (Abernathy et al. 2010; Day et al. 2015; Mintzer 2007).

Research examining the effects of alcohol consumption on working memory performance in humans has yielded inconsistent findings (Abernathy et al. 2010; Day et al. 2015; Mintzer 2007). Whereas some studies have observed significant effects of alcohol administration on working memory performance, many others have reported null findings (Abernathy et al. 2010; Day et al. 2015; Mintzer 2007). Mixed results may be attributable to a variety of factors. Qualitative reviews have acknowledged methodological differences across studies that make it difficult to interpret and summarize findings (Day et al. 2015; Mintzer 2007). Researchers have utilized a wide variety of behavioral tasks that can measure working memory processes in different ways (Abernathy et al. 2010; Day et al. 2015; Mintzer 2007). Varying methods have also been used to examine whether the effects of alcohol on working memory differ as a function of other methodological factors (e.g., alcohol doses, control conditions, sex/gender). Yet, findings regarding dose–response effects (Day et al. 2015), expectancy effects (Gundersen et al. 2008b; Saults et al. 2007; Spinola et al. 2017), and sex/gender interactions (Fama et al. 2020; Nixon et al. 2014) have been largely discrepant as well. Consequently, the acute effects of alcohol administration on working memory performance remain poorly understood.

Due to variation in results, sample sizes, and methodology across studies, the current understanding of alcohol effects on working memory may be considerably advanced by meta-analysis of existing data. By optimizing power and estimating robust effect sizes, meta-analytic techniques can account for different sources of study heterogeneity (Borenstein et al. 2011), which would help resolve the notable discrepancies in the literature. To our knowledge, the varied findings from this literature have never been quantitatively synthesized. Thus, the primary aim of this systematic review and meta-analysis was to evaluate and clarify the evidence for acute alcohol administration effects on working memory performance in experimental human studies. We also aimed to examine the moderating effects of working memory task type, dose (attained BAC), control-condition type (no-alcohol vs. placebo), and sex/gender composition.

Method

This review adhered to guidelines recommended by the Cochrane Collaboration (Higgins and Green 2011), the Centre for Reviews and Dissemination (Tacconelli 2010), and the PRISMA-P-2015 statement (Moher et al. 2015; Morton et al. 2011; Shamseer et al. 2015; Wong et al. 2006). Two independent raters conducted all review stages, and discrepancies were resolved via consensus or by consulting a third reviewer. A protocol was established and preregistered on PROSPERO (CRD42019121050).

Eligibility criteria

Eligible studies were peer-reviewed publications that included (1) healthy human samples; (2) an experimentally controlled administration of alcohol (not in combination with other substances) in a quantified dose; (3) a comparative no-alcohol/placebo control condition; and (4) an established experimental working memory behavioral task. Studies using clinical samples (e.g., alcohol use disorders) were excluded due to potential confounding factors associated with these populations, including tolerance and altered cognition (Bernardin et al. 2014).

Search procedure and study selection

Reviewers searched PubMed, MEDLINE, and PsycINFO from inception to December 2018 (eAppendix 1 in Online Resource). Reference lists of eligible studies were manually screened. Titles and abstracts were screened for eligibility after removing duplicate results. In accordance with

published recommendations (Beller et al. 2013) and our preregistered protocol, an updated search was performed in June 2021 prior to submitting the final manuscript for publication review. Full-text articles were screened further using inclusion/exclusion criteria. Both reviewers (SS, MD) agreed upon a final study list.

Working memory outcomes

Table 1 provides an overview of working memory tasks administered in each study. Established working memory assessments identified in our literature review included mental arithmetic, span (i.e., digit, operation, counting), letter-number sequencing, *N*-back, trail making test B, Sternberg memory scanning, self-ordered pointing, and visual working memory tasks. Additional methodological details for each task are presented in eAppendix 4 in the Online Resource.

Methodological quality

Study quality/validity was assessed using a 14-item scale (eAppendix 2 in the Online Resource) that was developed using PEDro guidelines (Sherrington et al. 2000), PRISMA-P 2015 recommendations (Moher et al. 2015), and Cochrane Collaboration criteria (Higgins et al. 2011). This scale was adapted from similar systematic reviews of experimental alcohol administration research (Thompson et al. 2017). Certainty in evidence was evaluated using GRADE[1] criteria to rate confidence in summary estimates (Meader et al. 2014).

Data extraction

Statistical information (e.g., means, standard deviations) for each working memory outcome was recorded to calculate effect sizes (Borenstein 2013). Additional data were recorded for moderation analyses, including working memory task type, dose(s) evaluated (attained BAC), control-condition type (placebo vs. no-alcohol), and sex/gender composition.

The following decisions were made when calculating effect sizes using available data: (1) When studies quantified a single working memory outcome using multiple scoring methods (e.g., reaction time, response accuracy), or had multiple working memory outcomes, a mean pooled effect size was computed for the overall meta-analysis (uncombined outcomes detailed in Online Resource 2). (2) Multiple alcohol dosages (e.g., low/moderate/high) examined within a single study were treated as individual comparisons. 3) When serial post-administration working memory measurements were taken, the measurement most proximal to the target BAC was identified, and corresponding statistics were extracted. (4) In studies that administered additional substances, data were extracted from alcohol-only conditions. (5) If studies divided participants into subgroups without reporting overall sample statistics, means and standard deviations were combined to restore original sample values. If studies recruited and examined subsamples (e.g., males, females) independently, then effect sizes for each group were input as separate comparisons (Borenstein et al. 2011). (6) For data presented graphically (e.g., charts), a validated data extraction software (WebPlotDigitizer v.4) was used to obtain values (Drevon et al. 2017; Rohatgi 2017). (7) When variability statistics were not reported, conservative estimates were back-computed using *p*-values and sample sizes, and subsequently used in effect size calculations (Borenstein 2013). If statistical significance was indicated as being less than a specific *p*-value (e.g., $p < 0.05$), a rounded *p*-value (e.g., $p = 0.05$) was used in these estimates. When significance was indicated but a specific *p*-value was not reported, a conservative *p*-value of 0.05 was used. (8) Effect sizes for matched groups were computed assuming a conservative correlation of 0.7 (Borenstein 2013; Borenstein et al. 2011).

Quantitative data synthesis

Effect size calculations and meta-analytic statistics were performed using Comprehensive Meta-Analysis v.3 (Biostat 2010). Given the methodological variability in how working memory outcomes are measured, Hedges' *g* was calculated to produce effect sizes in standard-score units. Random-effects meta-analyses of *g*-values provided summary estimates for each outcome. Interpretation of Hedges' *g* is similar to that of Cohen's *d*, with 0.20, 0.50, and 0.80 corresponding to small, medium, and large effects (Cohen 1988). Negative *g*-values indicated decrements in working memory, whereas positive values reflected working memory improvements.

Heterogeneity was assessed using Cochran's *Q* statistic. Higgins' I^2 was used to evaluate the proportion of variation across studies, with scores of 25%, 50%, and 75% corresponding to low, moderate, and high heterogeneity (Higgins and Thompson 2002; Higgins et al. 2003). The τ statistic provided a standard deviation estimate for different population effect sizes (Borenstein et al. 2011). Funnel plots and Egger's bias tests were used to assess publication bias (Egger et al. 1997).

[1] The GRADE approach considers questions of internal validity, inconsistency, indirectness, imprecision, and other concerns (e.g., publication bias) for each outcome. Certainty in evidence is evaluated using these domains, with very low-, low-, moderate-, or high-certainty ratings reflecting confidence in the accuracy of summary estimates.

Table 1 Characteristics of studies included in the systematic review

Study	Design	No. (% male)	Age	Control	Dose(s) evaluated (attained BAC)	Main outcomes
Ballard and de Wit 2011	C	11 (55)	25 (mean)	Placebo	0.020% 0.040%	Digit span
Balodis et al. 2007	B	152 (56)	19–31 (range)	No-alcohol*	0.085%	Ball counting task
Benedek et al. 2017	B	70 (46)	23 (mean)	Placebo	0.026%	N-back (RA)
Boha et al. 2009	C	32 (100)	22 (mean)	Placebo	0.015% 0.029%	Arithmetic (RT)
Boissoneault et al. 2014 (younger adults)	B	51 (61)	28 (mean)	Placebo	0.034% 0.057%	Visual working memory task$_1$ (RA/RT ratios)
Boissoneault et al. 2014 (older adults)	B	39 (38)	61 (mean)	Placebo	0.034% 0.052%	
Casbon et al. 2003	B	32 (50)	23 (mean)	No-alcohol	0.062%	*N*-back (S)
Colflesh and Wiley 2013	B	48 (100)	Not reported	No-alcohol	0.071%	Operation span task (span score)
Dry et al. 2012	B	56 (57)	27 (mean)	No-alcohol	0.048% 0.082% 0.100%	Self-ordered pointing task Trail making test B
Finn et al. 1999	B	116 (46)	21 (mean)	No-alcohol	0.078%	Digit span
Gevins et al. 2012	C	15 (47)	26 (mean)	Placebo	0.070%	*N*-back (RA; RT)
Gevins et al. 2013	C	15 (47)	31 (mean)	Placebo	0.070%	*N*-back (RA; RT) Digit span
Grattan-Miscio and Vogel-Sprott 2005	B	72 (72)	19–25 (range)	Placebo	0.074%	Sternberg memory scanning task (RA; RT)
Greenstein et al. 2010	B	60 (57)	31 (mean)	Placebo	0.067%	Counting span task (proportion correct)
Gundersen et al. 2008a	BP	45 (100)	27 (mean)	No-alcohol Placebo	0.080%	*N*-back (RA; RT)
Gundersen et al. 2008b	B	25 (100)	28 (mean)	No-Alcohol	0.020% 0.080%	*N*-back (RA; RT)
Hoffman et al. 2015	B	62 (42)	62 (mean)	Placebo	0.032% 0.053%	Visual working memory task$_1$ (RA/RT ratios) Trail making test B
Hoffman and Nixon 2015 (males)	B	49 (100)	28 (mean)	Placebo	0.037% 0.059%	Visual working memory task$_1$ (RA/RT ratios) Trail making test B
Hoffman and Nixon 2015 (females)	B	45 (0)	28 (mean)	Placebo	0.032% 0.055%	
Ilan and Gevins 2001	C	8 (50)	22–33 (range)	Placebo	0.100%	*N*-back (RA)
Kennedy et al. 1993	C	18 (100)	25 (mean)	Placebo	0.050% 0.100% 0.150%	Arithmetic (RA; RT)
Kleykamp et al. 2010	C	20 (40)	25 (mean)	Placebo	0.036% 0.089%	Sternberg memory scanning task (RA; RT)
Lechner et al. 2016	C	41 (57)	39 (mean)	Placebo	0.035% 0.079%	Trail making test B
Lewis et al.2019 (younger adults)	B	45 (40)	27 (mean)	Placebo	0.033% 0.055%	Visual working memory task$_1$ (RA/RT ratios)
Lewis et al.2019 (older adults)	B	45 (56)	63 (mean)	Placebo	0.033% 0.055%	
Paulus et al. 2006	C	10 (60)	23 (mean)	Placebo	0.070%	Visual working memory task$_2$ (RA; RT)
Pihl et al. 2003	B	41 (100)	21 (mean)	Placebo	0.080%	Random object span task (RA)
Rose and Duka 2008	B	32 (50)	21 (mean)	Placebo	0.073%	Spatial span task (RA)
Saults et al. 2007	B	72 (50)	21–30 (range)	No-alcohol Placebo	0.082%	Visual working memory task$_2$ Auditory working memory task

Table 1 (continued)

Study	Design	No. (% male)	Age	Control	Dose(s) evaluated (attained BAC)	Main outcomes
Schweizer et al. 2006	B	20 (100)	22 (mean)	Placebo	0.081%	Immediate working memory task (RA) Visual-spatial working memory task (RA)
Spinola et al. 2017	B	75 (48)	24 (mean)	No-alcohol Placebo	0.063%	Letter-number sequencing
Tarter et al. 1971	B	26 (100)	23 (mean)	Placebo	0.080%	Digit span
Tiplady et al. 2009	C	26 (46)	23 (mean)	Placebo	0.124%	Sternberg memory scanning task (RA; RT)
Trim et al. 2010	C	60 (50)	20 (mean)	Placebo	0.057%	Visual working memory task$_2$ (RA; RT)
Weissenborn and Duka 2003	B	95 (48)	22 (mean)	Placebo	0.059%	Self-ordered search task (RA)

For study: subscripts a and b were used to denote separate studies published by the same author in the same year; for design: C = crossover within-subjects design, B = between-subjects design, BP = balanced-placebo design; for outcome: *RA*, response accuracy; *RT*, reaction time; *S*, sensitivity; *RA/RT*, response accuracy/reaction time composite score (e.g., ratios); subscripts 1 and 2 were used to denote distinct visual working memory tasks developed by Gazzaley et al. (2005) and Luck and Vogel (1997), respectively

Moderator analyses

When significant heterogeneity was indicated, moderation analyses were conducted to test the influence of several factors on alcohol-induced working memory effects. Mixed-effects analyses were used to test categorical moderators, whereas meta-regression was used for continuous moderators. Working memory task type was explored as a moderator for tasks that had at least 3 comparisons, given the heterogeneity of working memory tasks used across studies. Attained BAC was investigated as a continuous moderator given that working memory effects may become more pronounced as a function of increasing alcohol dose (Dry et al. 2012). Additional moderators were control-condition type (placebo vs. no-alcohol controls) and sex/gender composition, given evidence of expectancy (Gundersen et al. 2008a) and sex/gender (Fillmore and Weafer 2004; Magrys and Olmstead 2014; Miller et al. 2009) effects on alcohol-cognition relations in the literature.

Results

Study inclusion

The searches yielded 6912 total results (see Fig. 1). Reviewers identified 3 additional studies by manually examining references (Gundersen et al. 2008a; Kennedy et al. 1993) and updating the search prior to submission for journal review (Lewis et al. 2019). After duplicate removal, 5723 records were reviewed, and 5685 were excluded. In total, 38 full-text articles were assessed for eligibility, of which 32 publications satisfied inclusion criteria and were retained for analysis.

Study characteristics

Study characteristics are presented in Table 1. The 32 retained studies examined 1629 participants in total, 59% of whom were male (669 females; 960 males). Eleven studies employed crossover (within-subjects) designs, 20 studies used between-subjects designs, and 1 study utilized a balanced-placebo design. For control conditions, 23 studies had placebo conditions, 6 had no-alcohol conditions (Balodis et al. 2007; Casbon et al. 2003; Colflesh and Wiley 2013; Dry et al. 2012; Finn et al. 1999; Gundersen et al. 2008a), and 3 studies (Gundersen et al. 2008b; Saults et al. 2007; Spinola et al. 2017) had both. All studies examined healthy participants and described verifying this with clinical screenings. For sample ages, 27 studies reported a sample average ($M = 29$; range = 20–63), 4 reported a range (Balodis et al. 2007; Grattan-Miscio and Vogel-Sprott 2005; Ilan and Gevins 2001; Saults et al. 2007), and 1 reported an upper limit (i.e., < 30; Colflesh and Wiley 2013). All studies administered alcoholic beverages using standardized procedures. Attained BAC levels reported in the eligible studies ranged from 0.015 to 0.150% ($M = 0.062\%$). Publication dates ranged from 1971 to 2019.

Independent study quality/validity ratings demonstrated excellent agreement across raters for total scores ($ICC = 0.98$), with the consensus being reached for 100% of discrepancies (Koo and Li 2016). Mean quality/validity scores were in the moderate-high range ($M = 11.6$ on a 0–14 scale; $SD = 1.44$), with 97% of studies describing

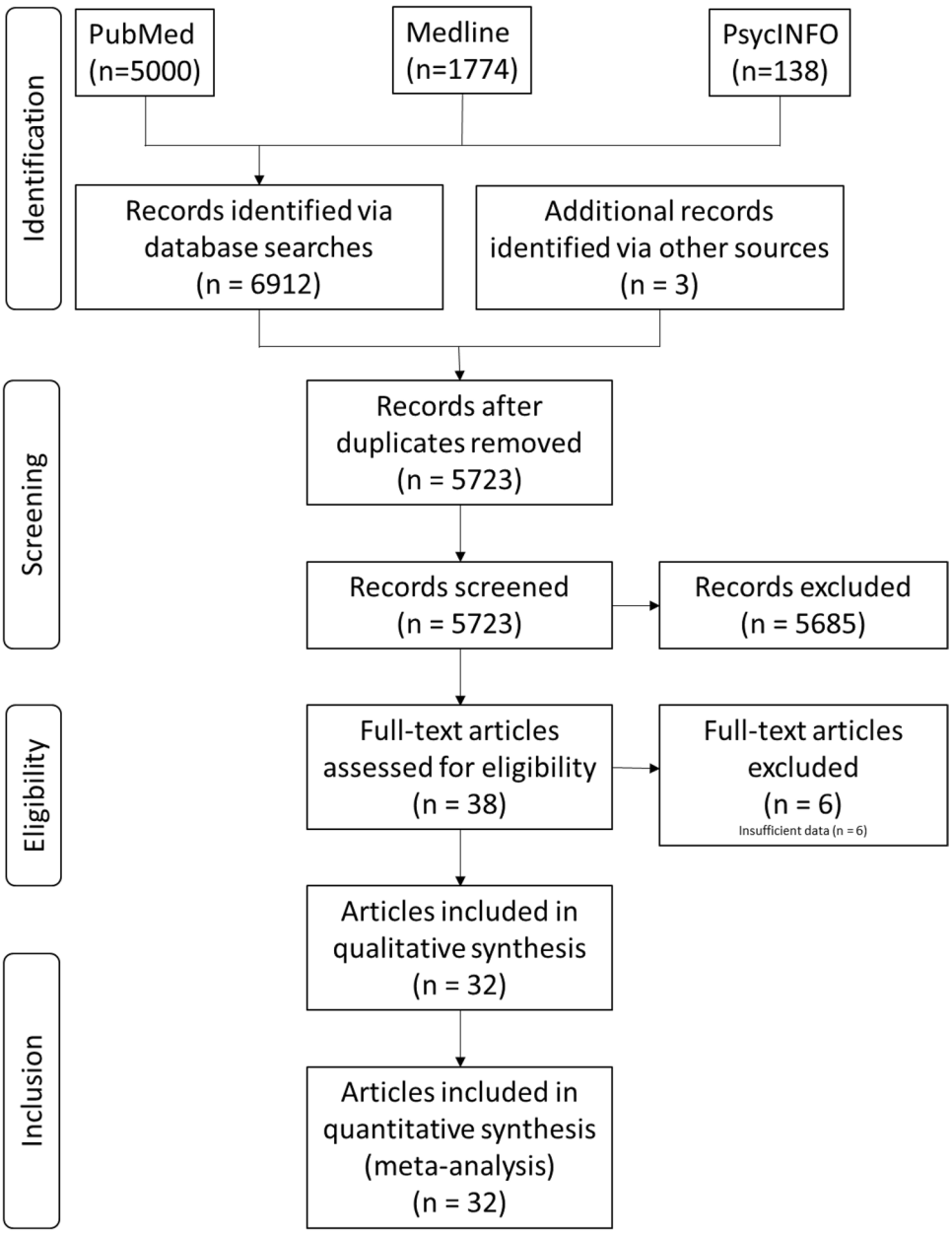

Fig. 1 Flow diagram of systematic search and study selection

randomization and 84% employing blinding procedures (eAppendix 2 in the Online Resource).

Overall meta-analysis

Thirty-two studies (1629 participants) provided sufficient data for 54 comparisons between alcohol and control conditions (i.e., placebo, no-alcohol). As presented in the forest plot in Fig. 2, random-effects meta-analysis produced an overall Hedges' g of − 0.300 (95% CI, − 0.390 to − 0.211, $p < 0.001$), indicating a significant, small- to medium-sized effect of alcohol administration on working memory.

Publication bias

Funnel plot asymmetry was not observed, and Egger's bias tests produced nonsignificant results ($p = 0.76$). Thus, publication bias was not indicated by these evaluations.

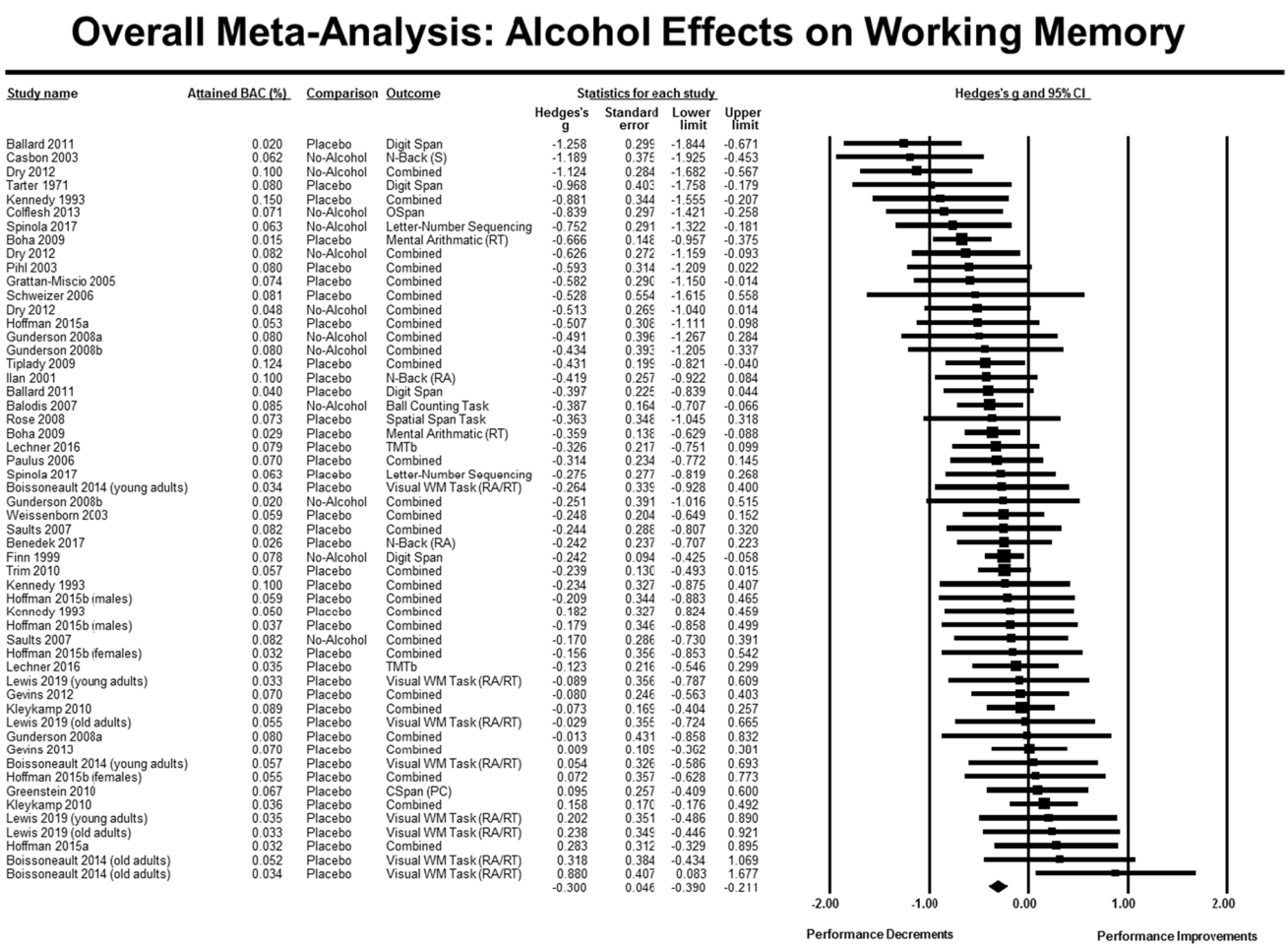

Fig. 2 Overall meta-analysis forest plot of alcohol effects on working memory

Moderator analyses

Significant heterogeneity was observed across comparison effect sizes ($Q = 87.46$, df_{53}, $p = 0.002$; $I^2 = 39\%$; $\tau = 0.20$). I^2 values suggested low-moderate heterogeneity (Higgins and Thompson 2002; Higgins et al. 2003) and moderation analyses were deemed appropriate.

Working memory task type The effects of alcohol on working memory appeared to differ significantly as a function of working memory task type ($Q = 15.23$, df_5, $p < 0.001$; see eFigure 1 in the Online Resource). Mixed-effects analyses revealed significant effects of alcohol administration on the *N*-back (Hedges' $g = -0.286$, $p = 0.018$), self-ordered pointing tasks (Hedges' $g = -0.620$, $p = 0.014$), span tasks (Hedges' $g = -0.376$, $p = 0.006$), and the Luck and Vogel (1997) visual working memory task (Hedges' $g = -0.235$, $p = 0.018$). Effect sizes for the Sternberg task (Hedges' $g = -0.271$, $p = 0.189$) and Gazzaley et al. (2005) visual working memory task (Hedges' $g = -0.095$, $p = 0.303$) were nonsignificant.

Dosage level After visually inspecting the data and examining meta-regression diagnostics, one comparison (Boha 2009: 0.015% BAC) was identified as an outlier and subsequently removed. Results from meta-regression analyses indicated that comparison effect sizes were significantly moderated by attained BACs (slope $= -3.252$, $p = 0.017$; see eTable 1 in the Online Resource). Higher BAC levels were significantly associated with greater decrements in working memory.

Control condition type The effects of alcohol on working memory tasks differed significantly as a function of control condition type (placebo vs. no-alcohol; $Q = 7.45$, df_1, $p = 0.006$; see eFigure 2 in the Online Resource). Employing either control type yielded significant effects. However, the effects of studies that used no-alcohol control conditions

(Hedges' $g = -0.534$, $p < 0.001$) were significantly larger than those of employed placebo-controlled conditions (Hedges' $g = -0.234$, $p < 0.001$).

Sex/gender composition Results from meta-regression analyses indicated that sex/gender composition significantly moderated the effects of alcohol administration on working memory (slope = −0.005, $p = 0.001$; see eTable 1 in the Online Resource). The effect size was significantly and negatively associated with higher percentages of male participants. Thus, alcohol-induced working memory decrements were larger in studies that had a greater percentage of males.

Discussion

This systematic review examined the acute effects of experimental alcohol administration on working memory outcomes using meta-analysis. Data were extracted from 32 experimental studies and provided 54 comparisons between alcohol and controls (e.g., placebo and/or no-alcohol controls) on measures of working memory. Pooling effect sizes revealed that acute alcohol administration produced small- to medium-sized decrements in working memory. A moderate GRADE rating was attributable to the inconsistency domain (i.e., significant heterogeneity estimates; eAppendix 3 in the Online Resource). Moderation analyses were performed to better account for heterogeneity and indicated that the effects of alcohol were moderated by working memory task type, alcohol dose, whether the research design included a no-alcohol and/or a placebo comparison condition, and sex/gender composition. The action of each moderator variable is discussed as follows.

Working memory task type The task-type moderating effects may be attributable to how experimental paradigms assess various working memory components. Researchers have hypothesized that working memory consists of maintenance (e.g., storage, rehearsal, matching) and manipulation (e.g., reordering, updating) process components (Abernathy et al. 2010; D'Esposito 2007; D'Esposito et al. 1999; Fletcher and Henson 2001; Veltman et al. 2003). Working memory manipulation is often considered to be a "higher-order" executive-related process (D'Esposito et al. 2000; Glahn et al. 2002; Kramer et al. 2014; Miyake et al. 2000; Smith and Jonides 1997). Whereas certain paradigms primarily measure maintenance processes, others are considered to be prototypical manipulation process assessments (Veltman et al. 2003). Accordingly, qualitative reviewers have recognized the need to investigate the effects of alcohol on distinct maintenance and manipulation processes (Mintzer 2007).

Interestingly, alcohol administration produced the most robust decrements in working memory tasks that involved manipulation processes. As seen in eFigure 1, alcohol administration was associated with significant decrements in the *N*-back, span, and self-ordered pointing tasks. Although the exact aspects of working memory measured by these tasks are still being elucidated, basic methodological information about each paradigm is provided in eAppendix 4. A large literature supports the use of the *N*-back as an assessment of manipulation processes (Friedman et al. 2006; Frost et al. 2021; Kirchner 1958; Owen et al. 2005; Veltman et al. 2003; Wager and Smith 2003; Watter et al. 2001). Similarly, complex span tasks have been shown to have high construct overlap with *N*-back tasks (Schmiedek et al. 2009; Wilhelm et al. 2013). Latent variable research has suggested that complex span and *N*-back tasks share strong associations with an updating factor (Wilhelm et al. 2013). As another prototypical manipulation assessment, the self-ordered pointing task (SOPT) is frequently considered to be sensitive to executive-related working memory deficits and frontal lobe pathology (Petrides 2000; Petrides and Milner 1982; Ross et al. 2007; Strauss et al. 2006). Consistently, the largest effect size observed in our task-type moderation analysis was for the SOPT (Hedges' $g = -0.62$). In contrast, effect sizes for the Sternberg task, which primarily evaluates maintenance processes (Altamura et al. 2007; Veltman et al. 2003), were nonsignificant.

Our task-type moderation analyses also yielded discrepant findings between two visual working memory tasks. Alcohol administration produced significant decrements in the Luck and Vogel (1997) visual working memory task, but not the Gazzaley et al. (2005) visual working memory task. Methodological differences between these two tasks may have contributed to discrepant effects. Importantly, the Gazzaley et al. (2005) task uses human faces as visual stimuli, whereas the Luck and Vogel (1997) task employs non-facial stimuli (e.g., shapes). Researchers have hypothesized that facial stimuli may be encoded and represented in specialized ways in visual working memory, relative to non-facial stimuli (Gambarota and Sessa 2019; Haxby et al. 2000, 2002). Faces convey complex information that may be processed by both domain-general visual working memory systems and/or specialized domain-specific components (Gambarota and Sessa 2019; Kanwisher and Yovel 2006). Working memory paradigms that employ non-facial stimuli may be more dependent on cognitive processes (e.g., executive functioning) and cortical areas (e.g., prefrontal cortex) known to be affected by alcohol administration (for review, see Abernathy et al. 2010). Distinctive working memory systems that process complex facial information may involve additional functional and structural components (e.g., fusiform face area) that may be less susceptible

to alcohol-induced disruption. Future research should examine whether the differential effects observed in this study are mediated by distinct facial processing systems.

Alcohol dose Alcohol dose was inversely related to working memory performance. Although dose–response effects are often hypothesized in working memory research, results reported throughout the experimental literature are highly variable (Day et al. 2015). Among studies that have administered multiple alcohol doses, some reported dose–response alcohol effects on working memory tasks (Dry et al. 2012), whereas others reported null findings (Gundersen et al. 2008a; Hoffman and Nixon 2015; Kleykamp et al. 2010). Some studies reported that effects occurred exclusively in either low-dose (Ballard and de Wit 2011; Boha et al. 2009) or high-dose (Lechner et al. 2016) conditions. Others reported moderated dose effects in specific experimental conditions (Boissoneault et al. 2014; Hoffman et al. 2015; Lewis et al. 2019). Given these inconsistent results, some researchers have suggested that working memory may not always be compromised by low and moderate alcohol doses (Hoffman and Nixon 2015). However, studies powered to detect larger effects at higher alcohol doses may be inadequately powered to detect smaller effects at lower doses. As evident in Fig. 2, the majority of reviewed studies reported null effects of alcohol on working memory tasks (72% of comparisons). Limited statistical power in individual studies may contribute to type 2 errors and inconsistent results across the literature. When statistical power and precision were enhanced using meta-analytic techniques, pooled effect size estimates were significant and robust. Our meta-regression results suggested that lower alcohol doses may confer smaller effects that require more statistical power to detect. Yet, none of the reviewed studies described performing power analyses. Future research would benefit from calculating and recruiting sample sizes that afford adequate power to detect small-sized effects at lower doses. Enhancing precision would allow more confidence in estimates and interpretations of dose-related data.

Control condition type Effect sizes significantly differed as a function of control condition type (no-alcohol vs. placebo). Although alcohol effects on working memory were significant for both control types, studies that employed no-alcohol control groups produced significantly larger effect sizes. Control condition types can differentially shape expectancies among study participants. Studies have shown that expectations for alcohol-related cognitive impairment can predict actual performance decrements (Fillmore et al. 1998), and expectancies have been shown to mediate the relation between alcohol administration and impairment severity (Fillmore and Vogel-Sprott 1996). Unlike no-alcohol controls, placebos may confer expectancies about alcohol-induced impairments, which may negatively affect working memory performance. Consequently, differences between no-alcohol and active conditions may be larger than comparisons between placebo and active conditions. Our moderation results support this hypothesis. Among the reviewed studies, 2 included both types of control conditions. Saults et al. (2007) reported that no-alcohol and placebo conditions were not significantly different in their study, possibly due to insufficient power. Spinola et al. (2017) reported pre-post changes in working memory that differed significantly between alcohol and no-alcohol control conditions, but not between alcohol and placebo conditions. Another study employed a balanced placebo design to determine the separate and combined effects of alcohol and expectancies on working memory (Gundersen et al. 2008b). Yet, alcohol administration and expectancy manipulations did not significantly affect working memory (Gundersen et al. 2008b). Our mixed-effects analyses enhanced power to detect effects by pooling estimates for each condition type across all the reviewed studies. Our results synthesized inconsistent findings and supported the hypothesis that placebo conditions may confer expectancy-induced working memory decrements. Accordingly, alcohol-induced working memory impairments may be more evident when no-alcohol control groups (versus placebos) are compared to active conditions.

Sex/gender composition Larger effect sizes (i.e., greater alcohol-induced working memory decrements) were significantly associated with higher percentages of male participants. Across the literature, studies examining sex/gender interactions with alcohol effects on working memory have reported inconsistent findings (Fama et al. 2020; Nixon et al. 2014). One study reported that women performed significantly better than men on a working memory task after alcohol administration (Greenstein et al. 2010). Another study described a complex interaction between sex, age, and dose, such that women evinced divergent working memory performance contingent on age and dose (Lewis et al. 2019). In contrast, many studies have reported null interaction effects for sex/gender (Boissoneault et al. 2014; Casbon et al. 2003; Hoffman et al. 2015; Saults et al. 2007; Weissenborn and Duka 2003). Methodological variability and limited statistical power have been implicated as possible sources of inconsistent findings (Fama et al. 2020; Miller et al. 2009; Nixon et al. 2014). Our meta-regression results suggested that males (vs. females) may experience greater alcohol-induced decrements in working memory. Nonetheless, a direct meta-analysis of sex/gender interaction effects in this review was precluded by a lack of data. Cumulatively, research would benefit from testing the

moderating effects of sex/gender in adequately powered samples. Reporting complete statistical information, even when findings are null, would permit a more direct meta-analysis of sex/gender interactions in cumulative reviews.

More broadly, research has yet to determine whether the acute effects of alcohol on other types of cognition are moderated by sex/gender (Fama et al. 2020; Nixon et al. 2014). Given the overlap between working memory and executive functioning (D'Esposito et al. 2000; Glahn et al. 2002; Kramer et al. 2014; Miyake et al. 2000; Smith and Jonides 1997), alcohol administration studies examining sex/gender interactions in other executive-related paradigms may offer valuable insights. Some reviewers have suggested that the cognitive effects of acute alcohol administration may be more evident in women (Fama et al. 2020; Miller et al. 2009). Miller et al. (2009) reviewed data from 7 of their experiments comparing the effects of alcohol on driving-related cognitive performance in men and women. Compared to men, women exhibited larger effects on tasks measuring response activation/inhibition, auditory discrimination, processing speed, and motor coordination. Although the authors computed effect sizes for each study, gender differences were not statistically confirmed via meta-analysis. Rather, the authors performed a non-parametric sign test showing that women displayed greater effect sizes more frequently than men (Miller et al. 2009). Although suggestive of a pattern, a significantly greater frequency of larger effect sizes does not indicate that the effect sizes obtained separately for men and women are statistically significantly different from one another. Given that Miller et al. (2009) reported performance as being highly correlated between men and women across their tasks ($r = 0.93$, $p < 0.01$), direct effect size comparisons via meta-analysis would be warranted to confirm gender differences. A more recent qualitative review concluded that findings across this literature are not consistent enough to warrant strong conclusions about sex differences (Nixon et al. 2014). In contrast to the findings by Miller et al. (2009), several alcohol administration studies have found stronger decrements among men on executive-related cognitive functions, including response inhibition (Fillmore and Weafer 2004), sustained attention (Magrys and Olmstead 2014), and working memory (Greenstein et al. 2010). In addition to numerous other factors (e.g., neurophysiology, pharmacokinetics, learning, expectanciesMiller et al. 2009; Nixon et al. 2014), the acute effects of alcohol on cognition may differ between men and women depending on the cognitive domain being assessed. Future meta-analytic reviews that synthesize results within other cognitive domains (i.e., beyond working memory) may further clarify the discrepant literature.

Strengths, limitations, and future directions

As the first meta-analytic review of alcohol effects on working memory, the current study has several noteworthy strengths. This review consolidates inconsistent findings throughout the literature to clarify the effects of acute alcohol administration on working memory performance. Published guidelines (Higgins and Green 2011; Moher et al. 2015; Morton et al. 2011; Shamseer et al. 2015; Tacconelli 2010) for conducting and reporting rigorous systematic reviews were followed, and a preregistered protocol was followed to enhance transparency. A highly sensitive search strategy was employed across three electronic databases. Two independent reviewers performed all stages of the review and demonstrated good inter-rater reliability on a validity measure used in other alcohol administration research (Thompson et al. 2017). The average quality/validity score across studies was moderate-high, and analyses did not suggest publication bias.

Despite its notable strengths, this systematic review is limited to experimental alcohol administration studies in healthy humans. Although experimental research is valuable for limiting threats to internal validity in controlled environments, navigating dynamic real-world situations would likely require more working memory resources. Studies that include methods in more naturalistic settings (e.g., ecological momentary assessment) would enhance generalizability (Tiplady et al. 2009). Furthermore, the current review cannot address the cumulative effects of alcohol use on working memory performance. The lack of data on clinical populations (e.g., alcohol use disorders), drinking status, and lifetime alcohol use histories is particularly limiting. Indeed, associations between chronic alcohol use and executive function deficits have been reported throughout the literature (Abernathy et al. 2010). Poorer performance on executive functioning measures has been observed in participants with alcohol dependence (Bechara et al. 2001), long-term use histories (Bernardin et al. 2014; Goldstein et al. 2004), and particular use patterns (e.g., binge drinking, Crego et al. 2010). Nonetheless, qualitative reviews have highlighted challenges with interpreting and summarizing inconsistent findings across studies on alcohol use patterns and executive functioning, primarily due to methodological heterogeneity (Day et al. 2015). Additional research is warranted and could yield valuable data to better resolve discrepant literature, especially if synthesized using meta-analytic techniques.

Despite examining specific moderators, our review has insufficient data to examine the influence of other important methodological factors that differed across studies. Alcohol doses varied widely, and few studies examined how alcohol may differentially affect working memory during ascending

and descending BAC limbs (e.g., Schweizer et al. 2006). Thus, the current review is limited in its ability to describe the effects of specific alcohol doses at different time points. Individual differences in tolerance may contribute to variable BAC limb effects (Maisto et al. 2018). More research is needed to characterize the time-course and dose–response of alcohol effects on working memory. Among the reviewed studies, several working memory paradigms were used infrequently, precluding these measures from being examined in our task-type moderation analyses due to limited data. Aside from the notable methodological heterogeneity between extant measures, the working memory processes reflected by different paradigms are not uniformly understood. These types of heterogeneity increase variance that limits power to detect effects and compare different features of working memory. Additional studies that use multiple paradigms could further clarify the effects of alcohol on distinct working memory processes. The literature was also limited in how studies have considered the important influence of age in the effects of alcohol administration on working memory. Future research would benefit from explicitly examining and describing how participant age relates to observed effects. Lastly, our review primarily focused on experiments that administered alcohol exclusively. Yet, a limited number of studies have examined the effects of alcohol on working memory when administered in combination with other substances, including caffeine (Benson et al. 2019), nicotine (Greenstein et al. 2010), cannabinoids (Ballard and de Wit 2011), and benzodiazepines (Kleykamp et al. 2010). Alcohol use with other substances is often the most common pattern of polydrug use (Earleywine and Newcomb 1997). Cross-sectional research has reported that among alcohol users, over one-third use other substances concurrently (Saha et al. 2018; Staines et al. 2001). Given this prevalence, more research is needed to better understand how working memory is affected by alcohol when used with other drugs. Nonetheless, results from the current meta-analytic review may clarify mixed findings reported throughout the literature.

As an important future direction, research is needed to investigate how alcohol-induced working memory impairments relate to compromised self-regulation, hazardous behavior, and negative drinking consequences. Impaired executive functions have been implicated as a possible mechanism underlying the relation between alcohol consumption and disrupted self-regulation (Giancola 2000; Giancola et al. 2010; Hull and Slone 2004; Lyvers 2000; Steele and Josephs 1990). Self-regulation failures may contribute to hazardous alcohol-related behaviors (e.g., risk-taking, aggression) and consequences (Hull and Slone 2004). As a critical executive function component, working memory may play an important role in these associations. Our results indicated that alcohol administration impaired working memory performance, particularly when executive-related manipulation processes were involved. Importantly, there is evidence that explicit external cues can help people overcome alcohol-related information processing deficits that often lead to self-regulation failures (Fillmore and Blackburn 2002; Fillmore and Vogel-Sprott 1997; Hoaken et al. 1998). Thus, explicating these relations further may inform interventions that mitigate the consequences of alcohol-related executive function deficits and self-regulation failures (Hull and Slone 2004).

Conclusions

Working memory is an important component of executive functioning that may underlie associations between problematic alcohol use and self-regulation failures. Meta-analysis revealed that alcohol administration may produce small- to moderate-sized decrements in working memory performance. Larger effects were observed in working memory tasks that involved executive-related manipulation processes, compared to paradigms that primarily assess maintenance processes. Alcohol-induced working memory impairments were also larger in studies that had higher alcohol doses, no-alcohol (vs. placebo) control conditions, and higher percentages of male participants. The cumulative research synthesized in this review has further characterized how alcohol affects working memory performance.

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Author contribution Suzanne Spinola (SS) and Martin J. De Vita (MD) made equal contributions and share co-first authorship. Stephen A. Maisto (SM) was the senior author. SS, MD, and SM conceived and designed the study. SS and MD searched and extracted the data. SS and MD performed the statistical analysis. MD and CG performed the quality assessment. All authors contributed to the drafting of the manuscript and the interpretation of the data. All authors approved the final version of the manuscript.

Declarations

Conflict of interest The authors declare no competing interests.

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