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Abstract

Dehydration (DEH) is believed to impair cognitive performance but which domains are affected and at what magnitude of body mass loss (BML) remains unclear. **PURPOSE:** To conduct systematic literature review and meta-analysis to determine the effect size (ES) of DEH on cognitive performance and influence of experimental design factors (e.g., DEH > 2% BML). **METHODS:** Thirty-three studies were identified, providing 280 ES estimates from 413 subjects with DEH ranging from 1-6% BML. Outcome variables (accuracy, reaction time), cognitive domains, and methods to induce DEH varied. ES were calculated using standardized mean differences and multivariate meta-analysis. **RESULTS:** Impairment of cognitive performance (all domains/outcomes) with DEH was small but significant (ES = −0.21; 95% CI: [−0.31, −0.11], $p < 0.0001$) with significant heterogeneity ($Q(279) = 696.0$, $p < 0.0001$; $I^2 = 37.6\%$). Tasks of executive function (ES = −0.24; [−0.37, −0.12]), attention (ES = −0.52; 95% CI: [−0.66, −0.37]), and motor coordination (ES = −0.40; [−0.63, −0.17]) were significantly impaired ($p \leq 0.01$) following DEH; and, attention/motor coordination was different ($p < 0.001$) from reaction time specific tasks (ES = −0.10; [−0.23, 0.02]). BML was associated with the ES for cognitive impairment ($p = 0.04$); consequently, impairment was greater ($p = 0.04$) for studies reporting >2% BML (ES = −0.28, 95% CI: [−0.41, −0.16] compared to ≤ 2% (ES = −0.14, 95% CI: [−0.27, −0.00]). **CONCLUSIONS:** Despite variability among studies, DEH impairs cognitive performance, particularly for tasks involving attention, executive function, and motor coordination when water deficits exceed 2% body mass loss.

Key Words: Hypohydration, Executive Function, Accuracy, Reaction Time

Introduction

Dehydration (DEH) has known adverse effects on the human body (1). It is well-documented that physical performance tasks (aerobic exercise, muscular endurance, occupational tasks, sport-specific tasks) are impaired with DEH (1–4). In contrast, whether cognitive performance is also susceptible to dehydration and at what threshold of body water loss is far less clearly defined (5). Cognitive performance is a measurable outcome (e.g., accuracy, reaction time) during tasks requiring decision-making, problem-solving, attention, judgement, memory or eye-hand coordination. Initial studies on DEH and cognitive performance suggested executive function and information processing were impaired following DEH of 2% BML (6, 7). However, these findings have not been uniformly supported in subsequent studies (8–10). No sole reason accounts for the equivocal findings within the literature, however, potential variables include differences across methods to elicit DEH (e.g., exercise, exercise-heat stress, fluid restriction, diuretics), the magnitude of DEH, and the specific cognitive task evaluated (11–13). While narrative reviews highlight potential factors influencing the cognitive responses to DEH (12–15), a quantitative analysis that systematically examines the effect of these variables is absent from the literature.

It is clear that severe levels of DEH (e.g., >8% BML) elicit discernible cognitive impairments (16, 17). Soldiers in adverse environments (e.g., desert heat with extended water restriction) have an impaired ability to navigate, successfully complete military operations, and, if DEH is severe enough, present with confusion and delirium (16, 17). Soldiers undergoing 5% BML (solid and liquid) during a 72 h training exercise had impaired (by 2-4 fold) vigilance, reaction time, attention, memory, and reasoning compared to their performance at rest (18). However, these field-based military studies inducing large magnitudes of DEH typically include other co-factors also known to alter cognitive performance, including sleep deprivation (19), hypoglycemia (20), and other physiological stressors (21).

Thus, there is no clear threshold established at what magnitude of DEH (e.g., ≥ 2% BML) cognitive impairments begin to occur. Because 2% BML elicits physical (e.g., aerobic) performance decrements (1) along with accompanying physiological compensation due to hypovolemia and increased plasma osmolality (5), some suggest cognitive impairments also begin to arise in parallel. Experimental evidence indicates impairments occur at 2% with exacerbated decrements in cognitive functions at 4% BML (6, 7), suggesting an association between body water deficits and impaired mental functioning. However, not all subsequent studies have supported this relationship, with a recent review (15) suggesting additional protective mechanisms for the brain to preserve cognitive functions until DEH reaches a higher threshold (e.g., ≥ 3% BML).

Therefore, our purpose was to perform a systematic review of the literature and utilize a quantitative technique (i.e., meta-analysis) to determine the impact of DEH on performance of cognitive tasks. Our primary aim was to examine potential experimental design factors (e.g., method to elicit and magnitude of DEH, and cognitive test domain) that may influence the effect size estimate. We hypothesize that, like previous narrative reviews, DEH will induce a small but significant impairment in cognitive performance. Second, we hypothesize that the magnitude of DEH will be significantly associated with the degree of cognitive impairment, observable at a minimum threshold (> 2% BML) similar to that of other physical performance measures.

Methods

A systematic review was conducted on the research literature for the effects of DEH and cognitive performance. Cognitive performance was operationally defined as any measurable outcome resulting from completion of a cognitive function task (e.g., reaction time, accuracy). The literature search was completed as of September 13, 2017. Searches were conducted in the following databases: PubMed, Medline, Psych Info, SportDiscus, ISI Web of Science, SCOPUS, ProQuest Theses and Dissertations, which collectively returned 8306 results (6591 without duplicates). References from relevant review articles were also examined (11, 13, 15, 22) for articles not uncovered previously. Search terms consisted of: (*hydration OR water loss OR weight loss OR hypovol* OR sweat loss) AND (cognition OR cognitive function OR cognitive performance OR executive function OR response time OR reaction time OR intelligence OR memory OR mood OR vigilance OR pattern recognition OR letter* OR processing) AND (adult* OR college student).

Inclusion Criteria

Studies meeting the following inclusion criteria were considered for review: i) the study was conducted on healthy (i.e., no clinical conditions) adults (≥ 18 y), ii) the study contained at least two time-points (within or between groups) when cognitive testing was completed following DEH and under a control condition, iii) changes in hydration status were reported with body mass loss (BML), and iv) cognitive performance variables (e.g., accuracy, reaction time) were reported. We did not extract data related to mood since this psychological construct did not fit the operational definition of cognitive performance with accuracy or reaction time outcomes. Studies not on healthy adults and those inducing chronic dehydration (beyond 72 h) were excluded from the analysis. Studies were not excluded, however, due to elements of the research design (e.g. subject familiarization protocols, randomization of trial order or type of control trial used for comparison).

Selection of Studies

A total of 6591 relevant publications were originally identified through the database searches. Of those, 6512 were initially excluded based on title and/or review of the abstract (PRISMA diagram, Figure 1). Therefore, the full text of 79 studies was reviewed for meeting the inclusion criteria. Of those 79 studies, 48 were excluded due to no control condition, weight loss induced by >3 d fluid restriction, no BML measure, and no behavioral measures of cognitive performance resulting from DEH. Our screening criteria resulted in a total of 33 articles to be included.

Data Extraction

Studies included in the meta-analysis were independently coded by a minimum of two reviewers. Discrepancies in data entry were discussed and a consensus reached. Means, standard deviations, sample size, and correlations (if available) for both DEH and control conditions for all cognitive tasks within the study were extracted. If a study included any treatment condition other than DEH and control, the data for those conditions were omitted. Each task was categorized into specific cognitive domains of: attention, executive function, memory (short-term, working, long-term), information processing, motor coordination, or reaction time specific tests according to previously published criteria (23, 24) and/or author description of the task. Cognitive outcome variables (e.g., reaction time, accuracy) were extracted for all effect sizes. If the outcome variable of a given cognitive test was not explicitly described as reaction time or accuracy, it was categorized according to the attribute most closely aligning (e.g., errors as accuracy, speed as reaction time). Study quality scores (e.g., PEDro) were not calculated as many of these studies omitted descriptions for specific design elements (e.g., blinding of subjects/therapists, group allocation) present in clinical trials for which these metrics were based upon.

Meta-Analysis

The extracted cognitive performance data were converted to a standard format by calculating the standardized mean change score or effect size (ES) using the *metafor* package for R (v1.9-9, *www.metafor-project.org*). In studies where the correlational data were not reported, r was estimated from the median correlation taken from studies with i) known DEH-control correlations (25) and studies reporting effect sizes, means, and standard deviations from which r could be calculated (26, 27). The known correlations (n = 15, range: 0.01 – 0.92) had a median r of 0.62. For the effect size estimate, Hedges *g* was employed to minimize the inherent bias of Cohens *d* to overestimate the effect size when standardized mean differences are used with small sample sizes (28). For all analyses, a negative ES represents that DEH impaired cognitive performance versus control conditions whereas a positive ES represents an improvement.

The studies in the meta-analysis assessed a wide array of cognitive domains, providing several dependent outcomes (i.e., multiple tests with accuracy and reaction time) available to extract as results. Multiple effect sizes are problematic for most conventional meta-analyses, as the dependent structure of results (e.g., decreased reaction time but increased accuracy) may confound and compromise validity of the results unless the covariance structure is known (29). Because of this, a multivariate (mixed-effects) meta-analysis was employed. Multivariate meta-analyses are appropriate when multiple related outcomes are reported within each study (e.g., both reaction time and accuracy for a given test or multiple tests of executive function) and the dependence structure is unknown (30). Multivariate meta-analysis, compared to other techniques, can control for multiple outcomes without necessitating study-wide averaging which can yield ES estimates that do not represent the range of study outcomes (30).

The meta-analysis was completed using the *rma.mv* function from the *metafor* package in R (*www.metafor-project.org*). The appropriate random effect structure was identified by fitting an intercept only model (no moderators) with multiple random effect configurations. Using the *anova* function within R, each different random effect configuration was compared. The best random effect structure was identified from the model yielding the lowest Akaike information criterion (AIC). This process resulted in a random effects model which allowed modeled between-study differences along with within-study differences based upon cognitive domains and outcome variables (accuracy, reaction time) assessed.

To assess the overall effects of DEH on cognitive performance, an intercept-only model was used. Subgroup analysis was completed using the *mods* option within the *rma.mv* function. A Q test was instituted to examine if moderator variables significantly impacted the effect size estimates. If the subgroup was categorical (e.g., ≤ or > 2% BML), the effect size estimates were compared to each other. If moderator variable was continuous (% BML), the slope was compared to zero using meta-regression. Publication bias of studies included within the meta-analyses was assessed using a Duval and Tweedie trim and fill correction funnel plot from the *trimfill* function within *metafor*. Because the *trimfill* function cannot analyze multivariate meta-analysis structures, a random effects meta-analysis model was utilized for this analysis. Across all comparisons, an alpha level of ≤ 0.05 was used to indicate statistical significance. As is common practice, ES (Hedges g) of 0.2, 0.5, and 0.8 were considered small, moderate, and large, respectively, while ES < 0.1 considered trivial (31).

Subgroup Analyses

We aimed to determine the influence of experimental factors on the overall ES using moderator analysis. A subgroup meta-analysis (i.e., meta-analyses comparing subsets of studies) was used to probe potential moderator variables such as the type of cognitive domain, type of performance outcome, method of DEH, or magnitude of DEH. In order to be considered a subgroup, we set a minimum of five studies in the category. Study design was examined by classifying either pre-post (e.g., measurements compared from baseline to after intervention) or crossover (e.g., matched trials on separate days). A majority of studies (m = 23) assessed multiple domains of cognitive performance. The cognitive domains compared were attention, executive function, information processing, memory, motor coordination, and reaction time-specific tasks. Outcome variable types (accuracy and reaction time) across all cognitive tasks were also compared since most tasks provided both accuracy and reaction time outcomes.

Methods to induce DEH were coded into the following categories: exercise, heat exposure (ambient temperature ≥27ºC), exercise-heat stress (exercise + heat exposure with ambient temperature ≥27ºC), or fluid restriction. Two studies (32, 33) induced DEH via both an exercise only and exercise plus diuretic trial. The administration of a diuretic did not significantly increase BM loss; therefore, both trials were averaged for the analysis. Due to the environment, both studies (32, 33) were subsequently categorized as exercise-heat stress protocols. Another two studies utilized fluid restriction plus exercise to induce DEH (27, 34). One study utilized a 15 h fluid restriction protocol followed by 45 min cycling at ~70% maximum effort in a temperate environment and was therefore classified as an exercise protocol (34). The other study (27) had subjects undergo a prolonged fluid restriction protocol before one measured condition followed by an exercise bout. In that case, the data point following exercise was classified as an exercise protocol.

DEH methods were also categorized into two classifications: with/without the addition of environmental heat stress and with/without exercise. The magnitude of DEH was also sub-grouped by cut point of ≤ 2 % or > 2 %BML to examine whether cognitive studies inducing sufficient body water losses typically observed to elicit physiological compensation (5, 35) had greater impairments (and parallel studies on physical performance). If information was provided about subject fitness level (based on either aerobic exercise testing or author description), this information was used to categorize subjects as sedentary, recreational, or highly fit (VO_2 max > 55 mL/kg/min). In the presence of a significant Q value, pairwise comparisons were made between different levels of the moderator variable with Bonferroni-Holm corrections.

Meta Regression

The magnitude of DEH (values ranging from 1.1 – 6.0% BML across individual studies) associated with cognitive task impairment was examined using meta-regression. Because each specific BML was coded, multiple levels of DEH per study were possible, even with small differences (e.g., 2.1 vs 2.2 %). Instances where raw BM measures were reported, a percent change score was calculated (%BML = (BMpost - BMpre) / BMpost). Aspects of environmental heat exposure (core temperature, duration of exposure > 27ºC) were also analyzed using meta-regression.

Results

Study Characteristics

Supplementary Table 1 (see Table, Supplemental Digital Content 1, Characteristics of 33 studies, http://links.lww.com/MSS/B301) presents the characteristics of each study in the analysis. The final sample consisted of 33 studies (m), all were published in peer reviewed journals except one (36) found in ProQuest. In total, there were 413 subjects and 280 effect sizes (k) with a median of 6 effect sizes per study (range: 1-36). All 33 studies utilized a repeated measures (within subjects) design with 11 and 22 using a pre-post or crossover design, respectively. Practice trials or subject familiarization with the cognitive tasks were reported for 24 studies (9 did not specify). Across all studies, the median BML incurred was 2.1% (min-max: 1.1 - 6.2%). Because DEH magnitude was determined based on %BML, nine studies had multiple levels within the study compared to 24 studies eliciting only one level of DEH. Sixteen studies elicited DEH via exercise-heat stress, seven using exercise only (no heat), three with heat stress only (no exercise), and four with fluid restriction only. Three studies utilized multiple methods of DEH.

The cognitive domains assessed following DEH were attention (m = 10; visual vigilance, test of variables of attention, monotonous driving task, oddball), executive function (m = 17; mental math, trail-making test, proof reading, grammatical reasoning, map recognition, logical relation test), memory (m = 18; digit span, match to sample, n-back test, repeated acquisition, story recall, word recognition, map recall, picture recall), reaction time specific (m = 16; simple/choice reaction time), information processing (m = 8; perceptive discrimination, target evaluation, critical flicker fusion test, substitution test, visual perception test, letter-digit substitution), and motor coordination (m = 5; unstable tracking, manual tracking test, psychomotor test, Groton maze chase). Approximately half of the studies (17 of 33) reported at least one significant cognitive outcome impairment following DEH.

Of the 33 total studies, 27 (81%) included only male subjects. When fitness level was measured/described, only recreationally (m = 13) or highly fit (m = 13) subjects were included (7 studies did not specify).

Overall Effect of Dehydration on Cognitive Performance

Figure 2 presents the overall averaged ES for all cognitive performance outcomes within each of the 33 studies reporting effects of DEH. Considerable variation was observed among studies, with individual study-averaged ES ranging from −1.25 to 0.75. Nine studies (27%) demonstrated a study-averaged positive ES or improvement in cognitive performance (one was significant) while twenty-three studies (73%) had negative ES (eight were significant). When including all studies and outcomes (m = 33, k = 280), DEH elicited a small but significant impairment in cognitive performance ($g = -0.21$, $p < 0.0001$, 95% CI: [−0.31, −0.11]). There was significant heterogeneity across studies ($Q(279) = 696.0$, $p < 0.0001$). The amount of total variance attributed to the total amount of within-study heterogeneity was low to moderate ($I^2 = 37.6\%$) while between study heterogeneity was low ($\tau^2 = 0.12$). Study designs which utilized pre-post measures (resting control) within the same trial ($g = -0.11$, 95% CI: [−0.29, 0.07]; $p = 0.25$) were not significant for cognitive impairments, although not significantly different ($p = 0.15$) compared to studies using crossover designs ($g = -0.26$, 95% CI: [−0.38, −0.14]) which did show cognitive impairments overall ($p < 0.001$).

The trim and fill analysis suggested two additional DEH studies observing a strong positive effect (g of ~0.6, 0.9) on cognitive performance would be needed in order to minimize publication bias. However, the theoretical addition of these two positive ES studies did not alter significance of the overall ES ($g = -0.17$, 95% CI: $[-0.29, -0.05]$, $p = 0.006$), although the ES was reduced to between small and trivial. It is also highly unlikely that such a “theoretical” positive finding in improved cognitive function due to DEH would have remained unpublished. A subgroup meta-analysis comparing published studies versus unpublished studies was not possible since only one study was unpublished.

Analysis of Moderator Variables

Cognitive Domains

Table 1 presents moderator variables for studies examining the effects of DEH on cognitive performance. DEH elicited a significantly greater impairment ($Q(1) = 5.6$, $p = 0.02$) in accuracy compared to reaction time outcomes across the range of cognitive tests in all studies. There was a significant effect ($Q(5) = 51.9$, $p < 0.0001$) of DEH when compared across the different broad categories of the cognitive domains assessed. Tasks assessing attention, executive function, and motor coordination had significant ($p \leq 0.01$) DEH-induced impairments but ES was not significant for information processing ($p = 0.36$), memory ($p = 0.11$), or reaction time specific tasks ($p = 0.14$). The subgroup analysis indicated a greater impairment in tasks of attention ($g = -0.54$, 95% CI: $[-0.69, -0.39]$; $Q(1) = 31.5$, $p = 0.001$) and motor coordination ($g = -0.40$, 95% CI: $[-0.63, -0.17]$; $Q(1) = 14.6$, $p = 0.01$) compared to reaction time specific tasks ($g = -0.10$, 95% CI: $[-0.23, 0.03]$). Figure 3 presents the Forest plots for the sub-group analysis between tasks requiring attention ($m = 10$, $k = 37$), motor coordination ($m = 5$, $k = 14$), and those specific tasks based upon reaction time ($m = 16$, $k = 50$). No other significant differences were found ($p > 0.05$) among the other categories (i.e., executive function, information processing, memory, and reaction time).

Level of Dehydration

Figure 4 presents the meta-regression results for all effect size estimates across the range of DEH. Overall, meta-regression revealed a significant association between the magnitude of DEH (% BML) (slope = 0.07, Q(1) = 4.0, $p = 0.04$) and decrements in cognitive performance, although the relationship ($R^2 = 0.003$) explained virtually none of the variance. Based on the sub-group analysis across all cognitive domains and outcomes, studies eliciting a BML >2% elicited significantly greater (Q(1) = 4.2, $p = 0.04$) cognitive impairment than studies eliciting ≤ 2% BML, although ES estimates for both sub-groups were significant (Table 1).

Other Factors

No significant differences in ES were observed between the sub-groups for methods to induce DEH (Q(3) = 0.7, $p = 0.87$). Three methods (exercise, exercise-heat stress, and fluid restriction) elicited significant ($p < 0.05$) cognitive impairment while heat stress alone did not ($p = 0.15$). Sub-group analysis (Table 1) indicated cognitive performance was not impaired to a greater extent ($p = 0.54$) when DEH was elicited with an element of environmental heat stress (heat stress or exercise-heat stress) compared to protocols without heat exposure (exercise only, fluid restriction). Furthermore, meta-regression analysis did not yield significant associations between core temperature ($p = 0.78$, $R^2 = 0.005$) or duration of heat exposure ($p = 0.70$, $R^2 = 0.001$) to cognitive performance in those studies with heat exposure. Likewise, sub-group analysis comparing dehydration methods using exercise to induce DEH (exercise, exercise-heat stress) were not different (Q(1) = 0.05, p = 0.83) in cognitive impairments compared to methods without exercise (Table 1). The subject level of fitness (Q(2) = 2.3, p = 0.31) did not differ among groups with both recreationally fit (p = 0.0001) and highly fit (p = 0.05) subjects experiencing significant cognitive impairment following DEH (Table 1).

Discussion

Dehydration is believed to impair cognitive performance and potentially increase workplace accidents and occupational risk (37). Although narrative reviews suggest dehydration may impair cognitive performance (11, 14), previous research has not uniformly supported this position (5). The current study employed a quantitative analysis of studies and objectively determined there is a significant effect of dehydration on cognitive performance. We also assessed the influence of several study design factors that contribute to this effect. Our meta-analysis supports previous hypotheses (15, 38) that some cognitive domains (i.e., attention, executive function, motor coordination) are more likely to degrade with DEH, especially when compared to lower-level tasks (i.e., reaction time) and also that the degree of cognitive impairment is associated with the magnitude of DEH.

The main finding of this study is that dehydration elicits a small but significant impairment on cognitive performance. This negative effect size aligns with narrative reviews suggesting dehydration may mirror the effects of other nutritional interventions by altering cognitive performance but only by a small degree (13). Furthermore, this significant finding occurred in the face of significant study heterogeneity, which has been repeatedly acknowledged in narrative reviews (13, 14), thus making a firm conclusion challenging. To this point, only 52% of studies (17 of 33) observed at least one statistically significant cognitive impairment following dehydration. A meta-analytic technique overcomes this limitation and enhances the ability to assess the impact of various experimental factors potentially contributing to the heterogeneity of results.

The second main finding of the current study was that dehydration does not affect all cognitive domains equally. Previous studies have demonstrated this experimentally (32, 34, 39) by observing significant cognitive impairments following DEH in some, but not all, cognitive domains. Some have also suggested higher-order cognitive domains may be impaired to a greater extent following dehydration (11, 14, 15, 38), although a proposed mechanism has not been identified. To our knowledge, this is the first comprehensive analysis to systematically demonstrate which cognitive domains may be more at risk following dehydration. We observed that tasks requiring attention and/or executive function were significantly more impaired following dehydration while others (e.g., information processing, memory, reaction time tasks) were not. Both attention and executive function are generally considered ‘higher-order’ cognitive domains (40) and, as such, indicate more complex cognitive processing may be impaired following dehydration. Previously, dehydration (-1.6% BML) elevated fronto-parietal brain activations during an executive function task (Tower of London) but without significant performance impairments (41), suggesting neural inefficiencies during task performance. Furthermore, because fronto-parietal activations appear integral to executive functioning (40), prolonged cognitive processing (required for tests of attention), may also be responsible for executive function impairments. The specific rationale as to why other cognitive domains are less affected is yet to be understood. Specific cognitive domains may require different brain regions and neurotransmitter systems for adequate processing (11), potentially making some brain areas (and cognitive domains) more susceptible to body water deficits.

We also observed that tasks utilizing motor coordination are significantly impaired following DEH to a greater extent than ‘lower-order’ cognitive tasks. This is an analogous finding to multiple reports indicating skilled gross motor task degradation (e.g., basketball skills) following dehydration (2, 4). The tasks contained within the motor coordination domain in this meta-analysis largely consisted of fine motor (e.g., finger, hand) movements in response to visual stimuli sensed within the frontal eye field (42). Motor coordination tasks require neural processing in similar brain areas to attention/executive function tasks (e.g., frontal lobe), but also elicit activations within the motor thalamus, cerebellum, and basal ganglia (43). Why motor coordination may be more significantly impaired by dehydration is not entirely clear. Because dehydration appears to degrade perceptual responses of sensory mechanisms (e.g., thirst, hostility) (44), it is possible the thalamus and basal ganglia, which also monitor these sensory systems, are uniquely challenged.

Along with differences in the effect of DEH on cognitive domains, we found accuracy is impaired more than reaction time outcomes. This may suggest a change in strategy to preserve performance. One study demonstrated this experimentally following prolonged cycling, observing increased errors with dehydration compared with faster reaction time (45) often referred to as the speed-accuracy trade-off (46). An alternate explanation is that dehydration simply impairs higher-order cognitive processes involved in decision making but, for reasons currently unclear, still elicit responses with similar temporal characteristics. Future studies might investigate how dehydration alters speed-accuracy cognitive strategies.

Another major finding of this study was that cognitive performance declined along with the magnitude of water deficit and specifically, based on the sub-group analysis, when above 2% BML. This finding is in agreement with individual studies observing this graded phenomenon (6, 7), but differs from others that have elicited large body mass losses (~4% BML) without cognitive performance impairments (9, 10). Furthermore, greater cognitive impairments were observed in studies eliciting a dehydration threshold sufficient to induce physiological compensation (> 2%) versus when compensation was unlikely (≤ 2% BML) (5, 35). Taken together, these findings suggest the hypovolemia (and subsequent physiological compensation) elicited by dehydration may at least be partially responsible for cognitive impairments and this effect is observed at increasingly greater body mass losses. However, the level of body water deficit alone explained virtually none of the variance (< 1%) in the ES estimates; thus, the mechanisms responsible for this effect are not entirely clear but likely relate to the multiple mitigating factors already cited (dehydration method, cognitive domain, outcome measure) when a composite ES is utilized. It is well accepted that human cognitive capacity (i.e., ability to accomplish cognitive processing) is limited (47), and, as such, cumulative task demands which exceed a threshold level in capacity may result in performance decline. It is possible that progressive body water deficits (with increasing hypovolemia and thirst sensory distraction) may incrementally limit cognitive capacity resulting from a variety of mechanisms including altered neurotransmitter levels (11, 48), or brain structures (41) known to be associated with degraded cognitive performance in aging and/or disease states (49).

Our analysis also attempted to rule out other factors influencing the impact of dehydration on cognitive performance. Because increased fitness may increase cerebral circulation and brain perfusion (50), it was believed highly fit subjects may be more resilient to cognitive decrements following dehydration. However, sedentary individuals were not recruited in these studies, or compared specifically to recreationally or highly fit subjects. Future studies might investigate this factor with sedentary versus highly fit individuals using a non-exercise dehydration protocol.

The method utilized to achieve dehydration also did not differentially influence the ES, although passive heating (without exercise) did not elicit significant cognitive impairments. This finding conflicts with narrative reports suggesting heat stress may be required to elicit cognitive deficits (15). Some have suggested that, when dehydration is coupled with exercise and/or heat stress, the 'true' effect of dehydration is confounded (11). Effect size estimates for all dehydration methods were small to moderate (~ −0.2 to −0.5), suggesting any obfuscation of the 'true' effect of dehydration on cognitive performance by multiple physiological stressors is likely minor. Furthermore, three of the 33 studies (27, 39, 51) have investigated multiple dehydration methods within a single study testing the same subjects and concluded similar results. Two studies reported cognitive impairments with both exercise and heat stress alone (39, 51) and another found no difference between fluid restriction or fluid restriction combined with exercise (27).

As has been suggested previously, meta-analyses have some inherent limitations (28). A meta-analysis does not allow for mechanistic explanations but can provide a framework to guide future investigations. While not directly assessed in this study, dehydration-mediated cognitive impairments may be influenced by affective changes such as altered mood (32, 33) or the presence/sensation of thirst (44, 52) contributing to the total allocation of neural resources. Mental exertion may also be elevated during cognitive testing (26, 41, 53); however, this has not always paralleled performance impairments. These perceptual measures have been reviewed previously (13), but merit future meta-analytic investigation. Another inherent limitation is that some studies (8, 39, 54, 55) omitted reporting data from non-significant tests following dehydration. It is also possible that not all studies were of similar quality in terms of randomization, double blinding, and convenience sampling. Thus, the impact of these limiting factors on the current meta-analysis is unclear, and we acknowledge conclusions may change as future studies appear in the literature.

In conclusion, we have identified that, despite many studies using different experimental protocols reporting a variable range of results, dehydration elicits a small, but significant impairment in cognitive performance. Furthermore, high-order cognitive processing (involving attention and executive function) and motor coordination appear more susceptible to impairment following dehydration compared to other domains involving lower order mental processing (e.g., simple reaction time). The magnitude of dehydration is associated with the impairment in cognitive performance, specifically notable when > 2% body mass loss. Thus, the threshold for the impact of dehydration on cognitive performance may be similar to that previously reported for the performance of physical exertional tasks (i.e., exercise).

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Conflict of Interest

All authors had no conflict of interest, including relevant financial interests, activities, relationships, and affiliations to declare relating to this manuscript. The results of the study are presented clearly, honestly, without fabrication, falsification, or inappropriate data manipulation. The results of the present study do not constitute endorsement by the American College of Sports Medicine.

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Figure Captions

Figure 1: PRISMA diagram depicting the systematic review protocol in determining the inclusion of studies within the meta-analysis.

Figure 2: Forest plot of effect size (ES) for all studies (m = 33) examining dehydration on cognitive performance. Negative ES (g) indicate dehydration impaired cognitive performance whereas positive effect size (g) indicates improved cognitive performance. Box size indicates the relative weight of each study attributed to overall ES and horizontal lines indicate 95% confidence intervals. Diamond indicates mean overall effect size with width corresponding to the 95% confidence interval.

Figure 3: Forest plot of studies examining sub-group analysis for the effect of dehydration on tasks utilizing different cognitive domains: attention (*top*), motor coordination (*middle*), and reaction time specific tasks (e.g., simple/choice reaction time, *bottom*). ES for attention (Q(1) = 31.5, $p < 0.001$) and motor coordination (Q(1) = 14.6, $p = 0.01$) were significantly greater than reaction time specific tasks. Negative ES (g) indicate dehydration impaired cognitive performance whereas positive effect size (g) indicates improved cognitive performance. Box size indicates the relative weight of each study attributed to overall ES and horizontal lines indicate 95% confidence intervals. Diamond indicates mean overall effect size with width corresponding to the 95% confidence interval.

Figure 4: Meta-regression analysis for the magnitude of body mass loss (%) and effect size (g) for cognitive task performance (negative values indicate impairment). Each outcome (n = 280) for all cognitive test variables is depicted by a circle, with the circle size representing the relative weight attributed to each effect size. The slope for the line of best fit (solid line) was significantly different from zero (p = 0.04). Dashed lines indicated 95% confidence interval around line of best fit.

Supplemental Digital Content

SDC 1: Supplementary_Table_revised_5_2.doc

Figure 1

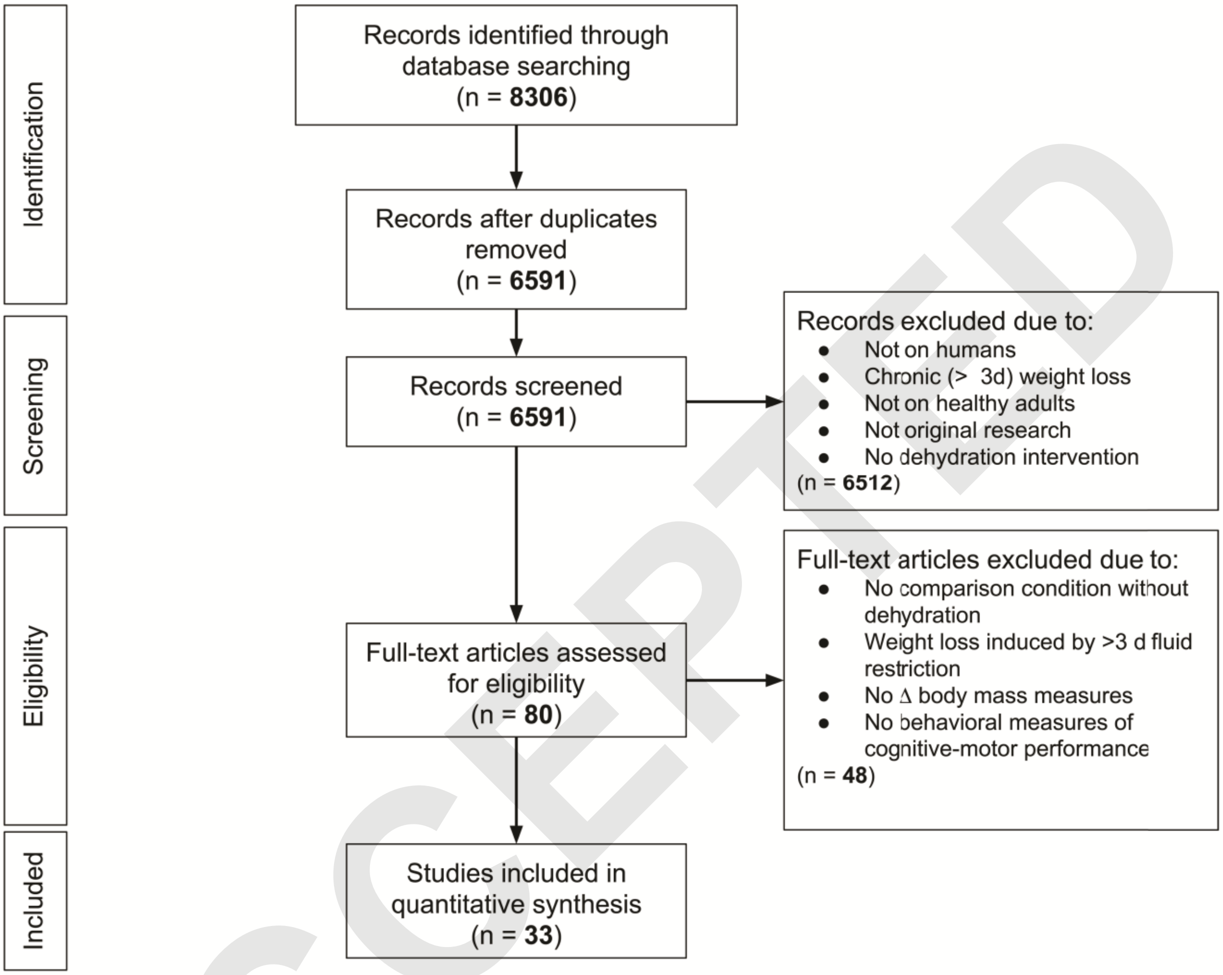
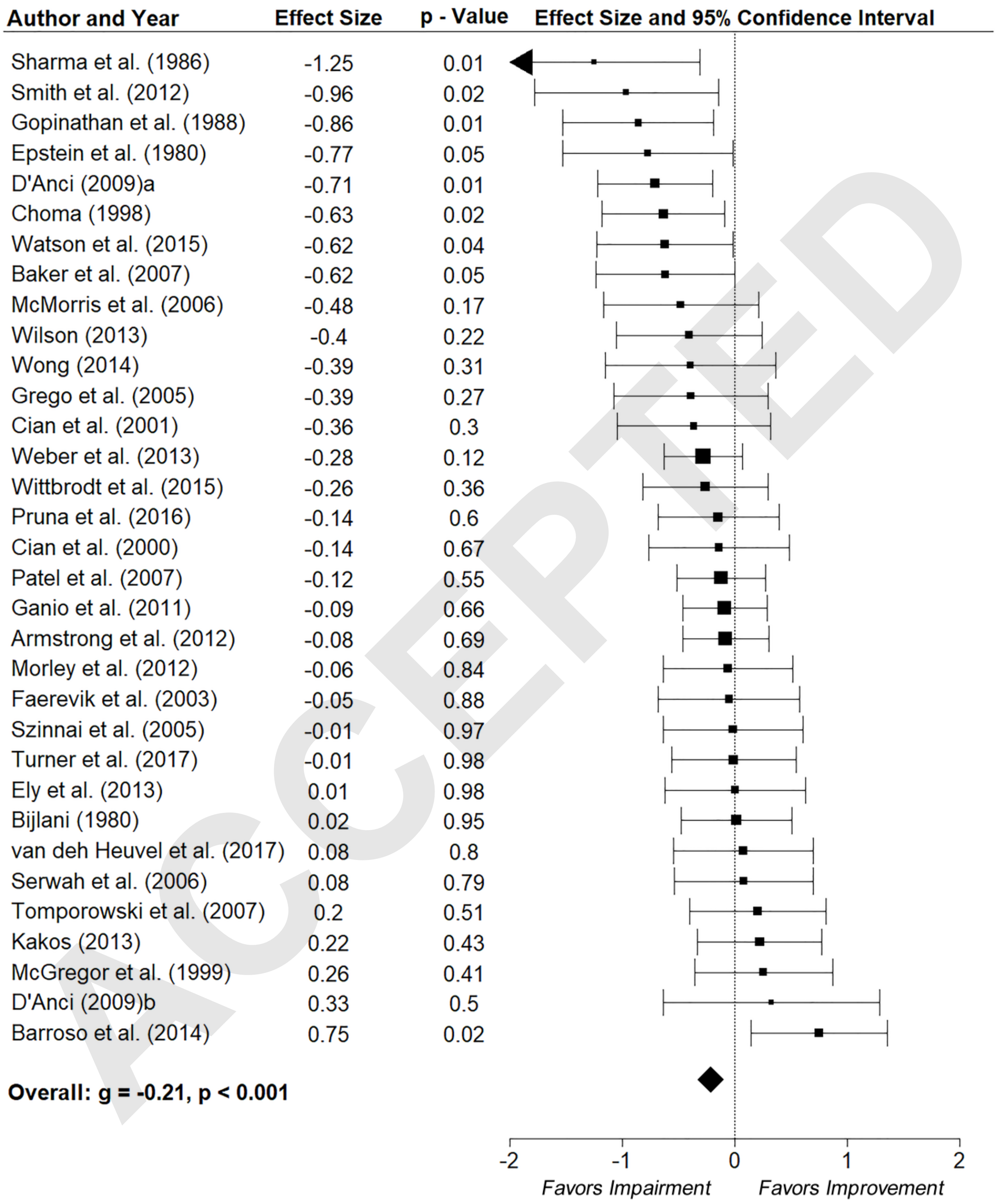

Identification
Screening
Eligibility
Included
Records identified through database searching (n = 8306)
Records after duplicates removed (n = 6591)
Records screened (n = 6591)
Records excluded due to:
Not on humans
Chronic (> 3d) weight loss
Not on healthy adults
Not original research
No dehydration intervention
(n = 6512)
Full-text articles assessed for eligibility (n = 80)
Full-text articles excluded due to:
No comparison condition without dehydration
Weight loss induced by >3 d fluid restriction
No Δ body mass measures
No behavioral measures of cognitive-motor performance
(n = 48)
Studies included in quantitative synthesis (n = 33)

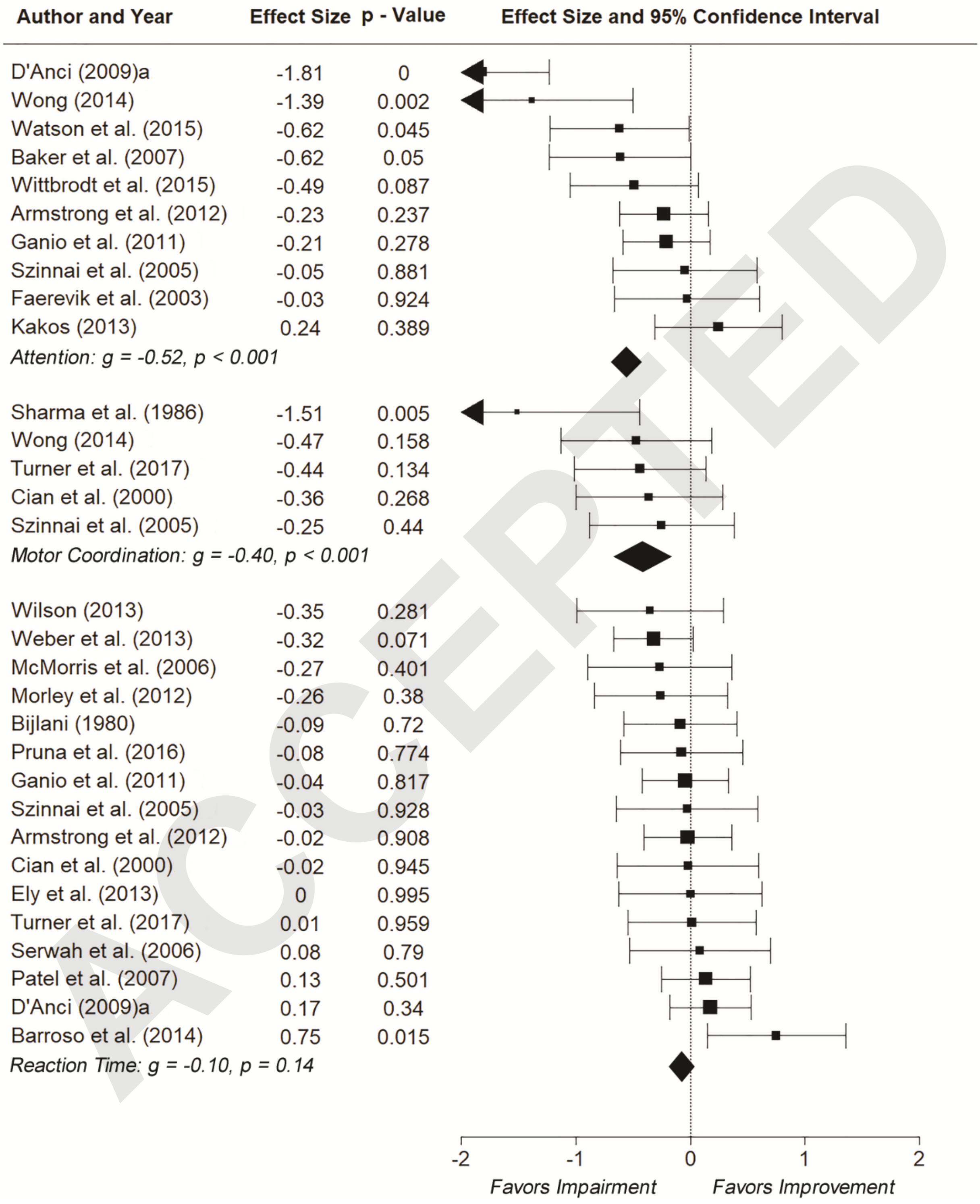
Figure 2



Author and Year	Effect Size	p - Value
Sharma et al. (1986)	-1.25	0.01
Smith et al. (2012)	-0.96	0.02
Gopinathan et al. (1988)	-0.86	0.01
Epstein et al. (1980)	-0.77	0.05
D'Anci (2009)a	-0.71	0.01
Choma (1998)	-0.63	0.02
Watson et al. (2015)	-0.62	0.04
Baker et al. (2007)	-0.62	0.05
McMorris et al. (2006)	-0.48	0.17
Wilson (2013)	-0.4	0.22
Wong (2014)	-0.39	0.31
Grego et al. (2005)	-0.39	0.27
Cian et al. (2001)	-0.36	0.3
Weber et al. (2013)	-0.28	0.12
Wittbrodt et al. (2015)	-0.26	0.36
Pruna et al. (2016)	-0.14	0.6
Cian et al. (2000)	-0.14	0.67
Patel et al. (2007)	-0.12	0.55
Ganio et al. (2011)	-0.09	0.66
Armstrong et al. (2012)	-0.08	0.69
Morley et al. (2012)	-0.06	0.84
Faerevik et al. (2003)	-0.05	0.88
Szinnai et al. (2005)	-0.01	0.97
Turner et al. (2017)	-0.01	0.98
Ely et al. (2013)	0.01	0.98
Bijlani (1980)	0.02	0.95
van deh Heuvel et al. (2017)	0.08	0.8
Serwah et al. (2006)	0.08	0.79
Tomporowski et al. (2007)	0.2	0.51
Kakos (2013)	0.22	0.43
McGregor et al. (1999)	0.26	0.41
D'Anci (2009)b	0.33	0.5
Barroso et al. (2014)	0.75	0.02

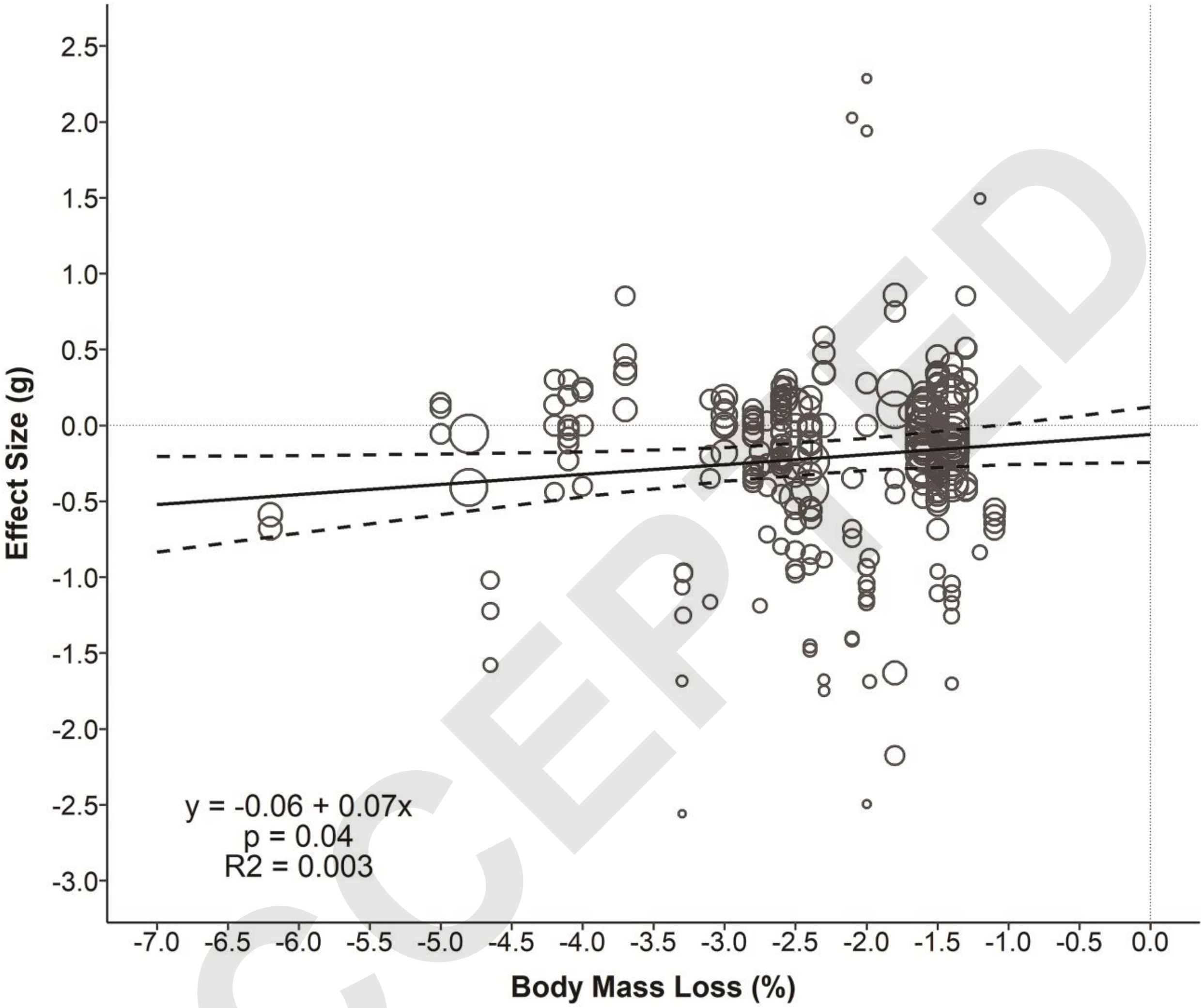
Overall: g = -0.21, p < 0.001

Figure 3



Author and Year	Effect Size	p - Value
D'Anci (2009)a	-1.81	0
Wong (2014)	-1.39	0.002
Watson et al. (2015)	-0.62	0.045
Baker et al. (2007)	-0.62	0.05
Wittbrodt et al. (2015)	-0.49	0.087
Armstrong et al. (2012)	-0.23	0.237
Ganio et al. (2011)	-0.21	0.278
Szinnai et al. (2005)	-0.05	0.881
Faerevik et al. (2003)	-0.03	0.924
Kakos (2013)	0.24	0.389
Attention: g = -0.52, p < 0.001		
Sharma et al. (1986)	-1.51	0.005
Wong (2014)	-0.47	0.158
Turner et al. (2017)	-0.44	0.134
Cian et al. (2000)	-0.36	0.268
Szinnai et al. (2005)	-0.25	0.44
Motor Coordination: g = -0.40, p < 0.001		
Wilson (2013)	-0.35	0.281
Weber et al. (2013)	-0.32	0.071
McMorris et al. (2006)	-0.27	0.401
Morley et al. (2012)	-0.26	0.38
Bijlani (1980)	-0.09	0.72
Pruna et al. (2016)	-0.08	0.774
Ganio et al. (2011)	-0.04	0.817
Szinnai et al. (2005)	-0.03	0.928
Armstrong et al. (2012)	-0.02	0.908
Cian et al. (2000)	-0.02	0.945
Ely et al. (2013)	0	0.995
Turner et al. (2017)	0.01	0.959
Serwah et al. (2006)	0.08	0.79
Patel et al. (2007)	0.13	0.501
D'Anci (2009)a	0.17	0.34
Barroso et al. (2014)	0.75	0.015
Reaction Time: g = -0.10, p = 0.14		

Figure 4



2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
-2.0
-2.5
-3.0
Effect Size (g)
y = -0.06 + 0.07x
p = 0.04
R2 = 0.003
-7.0
-6.5
-6.0
-5.5
-5.0
-4.5
-4.0
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
-0.5
0.0
Body Mass Loss (%)

Supplementary Table 1: Characteristics of the 33 studies examining the effects of dehydration (DEH) on cognitive performance. RF = Recreationally Fit, HF = Highly Fit (VO_2peak: > 55 mL/kg/min), NR = Fitness Not Reported, EHS = Exercise-Heat Stress (Ambient Temperature ≥ 27ºC), FR = Fluid Restriction, BM = Body Mass, M = Males, F = Females, T_c = Peak Core Temperature; [a] core temperature reported before cognitive testing, not peak of heat exposure. ND = No difference between DEH and control condition. NA = Data not available; NS = Not specified. All studies were repeated measures design.

Reference	Subjects / Fitness Status	BM Loss (%)	DEH Method	Study Design	Cognitive Task	Cognitive Domain	Practice	Reported Effects of DEH ($p < 0.05$)
Armstrong et al. (33)	25 F / RF	1.4	**EHS, EHS + Diuretic** (3 h; 28ºC, 49%RH) T_c = 38.1ºC	Crossover	Four Choice Reaction Time	Reaction Time	Y	ND
					Psychomotor Vigilance Test	Reaction Time		ND
					Matching to Sample	Memory		ND
					Grammatical Reasoning	Executive Function		ND
					Scanning Visual Vigilance	Attention		Increased False Alarms
					Repeated Acquisition	Memory		ND
Baker et al. (56)	11 M / HF	1,2,3,4 (Mean=2.5 %)	**EHS** (3h; 40ºC, 20%RH) T_c = 38.0ºC	Crossover	Test of Variables of Attention	Attention	Y	Decreased Vigilance
Barroso et al. (57)	12 M / HF	1.8	**EHS** (min NS;30ºC, 61%RH) T_c = NA	Pre-Post	Simple Reaction Time	Reaction Time	Y	Improved Reaction Time
Bijlani et al. (58)	14 M / NR	3	**EHS** (120-150 min; 41ºC, RH: NA) T_c = Rise of 1ºC	Pre-Post	Choice Reaction Time	Reaction Time	Y	ND
					Proof Reading Test	Executive Function		ND
Choma et al. (55)	14 M / HF	6.2	**FR**	Pre-Post	Digit Span, Story Recall	Memory	Y	Decreased Recall
Cian et al. (51)	8 M / HF	2.8	**Passive Heat** (2 h; °C/RH: NA) T_c = 37.4ºC **& Exercise**	Crossover	Picture Recall	Memory	Y	Shorter String Recall
					4-Choice Serial Reaction Time	Reaction Time		ND
					Perceptive Discrimination	Information Processing		Increased Reaction Time
					Digit Span	Memory		Reduced String Length
					Unstable Tracking	Motor Coordination		Greater Deviation
Cian et al. (39)	7 M / HF	2.6	**Passive Heat** (2 h; 47.5ºC, 45%RH)	Crossover	Picture Recall	Memory	Y	ND
					Choice Reaction Time	Reaction Time		ND

Reference	Subjects / Fitness Status	BM Loss (%)	DEH Method	Study Design	Cognitive Task	Cognitive Domain	Practice	Reported Effects of DEH ($p < 0.05$)
			T_c = 38.4ºC **& Exercise**		Perceptive Discrimination Digit Span Unstable Tracking	Information Processing Working Memory Motor Coordination		Longer Reaction Time Shorter String Recall Length ND
D'Anci et al. (59)a	16 M, 13 F / HF	1.8	**Exercise**	Crossover	Digit Span Simple, Choice Reaction Time	Memory Reaction Time	NS	ND ND
D'Anci et al. (59)b	12 M, 12 F / HF	1.2	**Exercise**	Crossover	Map Recall	Memory	NS	ND
Ely et al. (9)	32 M / NR	4.0 – 4.2	**EHS** (3h, 50ºC, 20%RH) T_c: 37.5-37.9ºC[a]	Crossover	Psychomotor Vigilance Task 4-Choice Reaction Time Matching to Sample Grammatical Reasoning	Reaction Time Reaction Time Memory Executive Function	Y	ND ND ND ND
Epstein et al. (60)	9 M / NR	2.4	**Passive Heat** (2 h; 50ºC, 40%RH) T_c = 38.5ºC	Crossover	Target Evaluation and Shooting	Information Processing	NS	Impaired Accuracy Greater Errors
Faerevik et al. (61)	8 M / NR	1.5	**Passive Heat** (3 h; 40ºC, 19%RH) T_c = 38.0ºC	Crossover	Vigilance Test Vienna Determination Unit Test	Attention Executive Function	Y	Increased Incorrect Reactions ND
Ganio et al. (32)	26 M / RF	1.6	**EHS, EHS + Diuretic** (3 h; 28 ºC, 42%RH) T_c = 37.7ºC	Crossover	Four Choice Reaction Time Psychomotor Vigilance Test Matching to Sample Grammatical Reasoning Scanning Visual Vigilance Repeated Acquisition	Reaction Time Reaction Time Memory Executive Function Attention Memory	Y	ND ND Slower Response Time ND Increased False Alarms ND
Gopinathan et al. (6)	11 M / RF	1,2,3,4	**EHS** (Time: NA; 45ºC, 30% RH) T_c = NA	Crossover	Serial Addition, Trail-Marking Test Word Recognition	Executive Function Short Term Memory	Y	Decrease Correct (Addition) Reduced Performance (Trail) Less Correct Responses
Grego et al. (45)	8 M / HF	3.1	**Exercise**	Pre-Post	Map Recognition Critical Flicker Fusion Test	Executive Function Information Processing	NS	Impaired Accuracy Faster Reaction Time Decreased Perception
Kakos (2013) (36)	11 M / RF	2.6	**EHS** (2 h; 38ºC, RH: NA)	Pre-Post	Running Memory Continuous Performance Task	Attention	Y	ND

			T_c = 37.9ºC		Logical Relations	Executive Function		ND
McGregor et al. (62)	9 M / HF	1.3, 2.4	**Exercise**	Pre-Post	Mental Concentration Test	Information Processing	Y	ND
McMorris et al. (63)	8 M / RF	2.8	**EHS**	Crossover	Random Movement Generation	Memory	Y	Worse Test Score
			(2 h: 36ºC, 75%RH)		Choice Reaction Time	Reaction Time		ND
			T_c rise = 1.1ºC		Corsi Block Tapping	Memory		ND
Morley et al. (64)	10 M / HF	1.6	**EHS**	Pre-Post	Psychomotor Vigilance Task	Reaction Time	NS	ND
			(50 min; 33-35ºC, %RH: NA)		Repeatable Episodic Memory Task	Memory		ND
			T_c = 39.0ºC					
Patel et al. (34)	24 M / NR	2.5	**FR + Exercise**	Crossover	Simple reaction Time	Reaction Time	NS	ND
					Math Processing,	Executive Function		ND
					Standardized Assessment of Concussion			ND
					Match to Sample Task,	Memory		Impaired Accuracy
					Sternberg Memory Task			ND
Pruna et al. (65)	12 M / HF	2.4	**Exercise**	Crossover	Visuomotor Training Device	Reaction Time	Y	ND
					Serial Sevens Test	Executive Function		ND
Serwah et al. (66)	8 M / RF	1.7	**EHS**	Crossover	Choice Reaction Time	Reaction Time	Y	ND
			(78 min; 31ºC, 63%RH)					
			T_c = rise of 1.8ºC					
Sharma et al. (7)	8 M / RF	1, 2, 3	**EHS**	Crossover	Psychomotor test	Motor Coordination	NS	Decreased Score at ≥ −2% BM
			(min NA; 43ºC, 45%RH)		Substitution Test	Information Processing		Fewer Correct at ≥ −2% BM
			T_c = 37.6, 37.8, 38.0ºC		Concentration Test	Memory		Fewer Correct at ≥ −2% BM
Smith et al. (67)	7 M / RF	1.5	**FR**	Crossover	Golf-Specific Cognitive Ability	Executive Function	NS	Impaired Distance Judgement
Szinnai et al. (53)	8 M, 8 F / NR	2.6	**FR**	Crossover	Oddball Paradigm	Attention	Y	ND
					Serial Addition Task,	Executive Function		ND
					Stroop Word-Color Test			ND
					Manual Tracking Test	Motor Coordination		ND
					Choice Reaction Task	Reaction Time		ND

Reference	**Subjects / Fitness Status**	**BM Loss (%)**	**DEH Method**	**Study Design**	**Cognitive Task**	**Cognitive Domain**	**Practice**	**Reported Effects of DEH (p < 0.05)**
Tomporowski et al. (38)	11 M / HF	1.3, 2.3, 3.7	**EHS**	Pre-Post	Executive-Processing Task	Executive Function	Y	Improved Switch Costs,

			(15-120 min; 30ºC, 40%RH)					Increased Switch Trial Errors
			T_c = 37.7, 38.4, 38.8ºC		Brown-Peterson Test	Memory		ND
Turner el al. (68)	11 F / RF	1.5	**EHS**	Crossover	Detection Task,	Reaction Time	Y	ND
			(2 h; 34ºC, <10%RH)		Identification task			ND
			T_c = NA		Groton Maze Chase Test,	Motor Coordination		ND
					One Card Learning Task,	Memory		ND
					One & Two Back Task,			ND
					Paired Associate Learning			ND
					Groton Maze Learning Test,	Executive Function		ND
					Set Shifting Test			ND
van den Heuval (69)	8 M / NR	3,5	**Passive Heat**	Crossover	N-Back Test	Memory	Y	ND
			(3.5 h; 39-41ºC Water)		Visual Perception Task	Information Processing		ND
			T_c = 37.0-37.2ºC^{a}					
Watson et al. (26)	11 M / NR	1.1	**FR**	Crossover	Monotonous Driving Task	Attention	Y	Greater Errors after 30 min
Weber et al. (27)	32 M / HF	2.4, 4.8	**FR, FR + Exercise**	Pre-Post	Simple Reaction Time	Reaction Time	NS	ND
						Executive Function		ND
Wilson et al. (70)	8 M / RF	1.8	**Exercise + Sweat Suit**	Crossover	Simple Reaction Time	Reaction Time	Y	ND
			(45 min, 20ºC, NA%RH)		Go-No-Go Task	Executive Function		ND
			T_c = NA					
Wittbrodt et al. (25)	12 M / RF	1.5	**EHS**	Crossover	Letter-Digit Substitution,	Information Processing	Y	ND
			(50 min; 32ºC, 65%RH)		Pattern Comparison			ND
			T_c = 38.2ºC		Perceptual Vigilance	Attention		ND
					Trail Making Test	Executive Function		ND
					Match-to-Sample	Memory		ND
Wong et al. (54)	10 M, 9 F / RF	1.4 – 2.1	**EHS**	Pre-Post	Detection Task	Motor Coordination	Y	Decreased Speed
			(60 min; 29ºC, 71%RH)		Identification Task	Attention		Decreased Performance
			T_c = NA		Visual Leaning Task,	Memory		Increased Speed and Decreased Accuracy in Males
					Working Memory Task			ND
					List Based Task			Decreased Accuracy