How does fasting affect cognition? An updated systematic review (2013-2020)

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Abstract

Introduction: The goal of this review was to provide an update on the literature examining how voluntary, temporary abstention from eating impacts cognitive function.

Methods and Results: We evaluated peer-reviewed articles published between August 2013 and January 2021 that assessed adults, included a measure of cognitive functioning with neutral stimuli, and compared individuals in a fasted state to individuals in a fed state (either within- or between-subject designs). Nineteen articles (21 studies) met inclusion criteria. Sample sizes, fasting methods, and tasks varied across studies. Review of studies indicated that fasting was associated with deficits in cognitive functioning; few studies indicated a benefit in cognitive functioning following a single voluntary fast.

Summary: The heterogeneity and rarity of available studies limits the conclusions that can be drawn. Several crucial psychosocial and sociodemographic moderators remain unexplored. Recommendations for future work are discussed.

Keywords: starvation, intermittent fasting, dieting, executive functioning, attention

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Introduction

Historically, fasting (i.e., temporarily and voluntarily abstaining from eating) was practiced largely for religious observance and/or political protest [1, 2]. In high-income, high-resource environments, individuals are less likely to fast for sociopolitical or religious purposes and are more likely to do so for cosmetic (e.g., weight loss or body shape manipulation) or medical reasons (e.g., preceding anesthesia) [1, 3]. In the last decade, long-term engagement in routine fasting (i.e., *intermittent fasting*, *time restricted eating*, and *alternate day fasting*) has been proposed as an intervention for, or for prevention of, a host of conditions including obesity [4], metabolic disorders [5, 6], cancer [7, 8], epilepsy/seizures [9], and sleep disorders [10, 11]. Long-term intermittent fasting is also hypothesized to slow or reverse symptoms of neurodegenerative disorders [12-15] and improve or accelerate recovery from traumatic brain injury [16], ischemic stroke [17], and spinal cord injury [18]. Fasting is thought to improve symptoms of psychological distress including pain management [19], depression, stress, and anxiety [20, 21]. However, fasting may also have negative consequences, especially on cognitive functioning.

In 2014, our team published a systematic review of the effects of acute (one-time) fasting on cognition [22]. We identified 10 articles that examined cognition in healthy, briefly fasted adults using neutral (non-food) stimuli. At the time, researchers had identified several impaired cognitive processes in individuals with eating disorders, namely impaired executive functioning [23-26]. In our review, we aimed to disentangle the impacts of starvation on cognitive impairment. The results suggested there were too few high-quality studies and methods were too heterogeneous to make firm conclusions about the impact of fasting on neurocognitive functioning. Dependent variables were inconsistent and confounding variables were common. It was clear at that time that more work was needed to understand the impact of fasting on neurocognition. The timing of the review was fortuitous. The popularity of fasting exploded shortly thereafter and academic interest in its physiological and cognitive impacts likewise increased [27]. A review of publications containing "fasting" and "cognition" in the title since 2000 indicates a linear and statistically significant increase in publications each year.

The purpose of the present review is to provide an update to the literature regarding the impact of fasting on cognitive function. Included are studies published since we conducted our original searches, namely August 2013 to January 2021. Our goal was to include studies of short-term experimental fasting (building on the results of our prior review) and expand to longer term fasting (such as intermittent fasting). The implications of this update include providing guidelines for future research focusing on the role of fasting on cognitive functioning as well as clinical implications.

Methods

The following search terms were entered into PsycINFO, CINAHL, and PubMed: "((fasting, caloric restriction, food restriction, hypoglycemia, food deprivation, hunger, intermittent fasting) AND (Stroop, color word interference, tower, tower task, trails, trail making, Brixton, CPT, continuous performance task, WCST, Wisconsin Card Sorting, card sorting, set-shifting, cognitive flexibility, tapping test, reaction time, Delis Kaplan, DKEFS[1]))." We restricted the search to peer-reviewed articles published in English since 2013 to the time of search (January 2021). Additionally, we used the "advanced" function of Google Scholar to

[1] i.e., the Delis-Kaplan Executive Function System (DKEFS) [28]. This standardized assessment battery is frequently used in studies of executive functioning, thus we included it by name in order to capture studies that employed it to examination cognitive performance.

identify additional articles and reviewed reference sections of related eligible and ineligible manuscripts. Abstracts were extracted and reviewed according to the steps outlined below.

Inclusion and Exclusion Criteria. The inclusion and exclusion criteria were nearly identical to our previous review [22]: the study must contain at least one group of healthy human participants (i.e., no diagnosed physical or psychological disorder that could interfere with cognitive processing), aged 18 years or older, that fasted (voluntarily and temporarily abstained from eating) via explicitly stated procedures. Studies must also have included cognitive tests with behavioral data analyzed and/or descriptive data presented so that our team could analyze or verify the findings. Standalone neuroimaging data were excluded. Unlike our previous review [22], we omitted religious fasting as these tend to involve an implementation of a "fast" that diverge from the dieting literature [29, 30]. Religious fasting also has psychosocial elements and rituals that may impact cognition [30, 31]. Additionally, we included studies that used ingestion of a glucose beverage as a control condition since an increasing number of studies include this method as a comparison to fasting. Evidence shows that ingesting even small amounts of glucose in a fasted state can impact physiology and cognition similarly to eating [32, 33]. We had no inclusion or exclusion criteria specific to water ingestion, duration of a fast, nor the number of fasts the participant completed (i.e., fasting could have been short- or long-term or conducted multiple times akin to intermittent fasting so long as a fasted and non-fasted condition were compared).

Selection and Review Strategy. All retrieved abstracts were uploaded into Covidence, a program designed to organize and manage systematic reviews (Veritas Health Innovation, Melbourne, Australia; www.covidence.org). Figure 1 presents the PRISMA diagram depicting flow for study selection. Articles were randomly assigned to pairs of reviewers (each author of this manuscript also served as a reviewer). Both assigned reviewers needed to agree that the article had potential to be included in order to advance it to full text review. When there was a disagreement, a third reviewer resolved the conflict.

Data Extraction. A total of 21 studies within 19 articles met all inclusion criteria, with a total of 50 comparisons of fasting vs. control conditions. Data for each measure were extracted by two different reviewers per study and compared using REDCap, a web-based database system [34]. If there was a disagreement, a third reviewer identified the correct information. If food-related or emotional stimuli were used in a study, we extracted the appropriate available data (e.g., the M and SD of accuracy and reaction time) to neutral stimuli and compared fasted and non-fasted conditions using *t*-tests. Similarly, we used descriptive statistics, when available, to confirm a study's presented findings and/or conduct simple comparisons of fasted and non-fasted conditions within more complex models. If not presented in the article, we requested these data from authors. Table 1 contains information regarding sample size, experimental design, and duration of fasting for each study. Table 2 reports each domain of neurocognition, the tasks used to assess it, and the impact of fasting on performance.

Results

Overview of the studies

There are several notable trends in the included studies. All studies featured acute fasting and none included long-term fasting despite setting our inclusion criteria specifically to capture the latter type of study. The lack of studies addressing the impact of long-term fasting on cognition was surprising and is a notable gap in the literature. Of the 21 studies included in this review, 16 (76%) used a within-subjects design or similar (i.e., cross-over or within-mixed). Sample sizes ranged from 10-150 participants. About half (n = 10, 48%) contained fewer than 40 participants and about a quarter (*n* = 5, 24%) contained fewer than 20 participants. Only eight studies (38%) in the sample included a power-analysis (one was post-hoc), of which four were studies with 21 or fewer participants. Thus, it is unclear if analyses were adequately powered, even in the case of within-subjects designs.

Most studies utilized convenience samples, often undergraduates. The samples across all studies were primarily women, seven samples were entirely women. Four studies [35-38] included gender, Body Mass Index (BMI), and/or baseline IQ as covariates, which is a notable strength. One study compared older adults to younger adults [38]. No other studies analyzed sociodemographic variables. No studies reported racial/ethnic composition or socioeconomic status of their samples. Research designs, recruitment methods, fasting duration, and fasting restrictions varied greatly and were reported inconsistently. Fasting durations ranged from 3 to 48 hours (the modal duration fell between 8-12 hours). Within-subject designs featured washout periods ranging from less than one hour to two weeks, with five not reporting this information. The control conditions included ingestion of glucose mixed with water, commercially available milk, juice, soft drinks, and athletic drinks, breakfast as usual, a standardized meal (including protein bars and/or protein shakes) or were unreported. In short, although these studies were published after late 2013, there are still notable limitations that impede generalizability, validity, and replicability.

Psychomotor Ability

Psychomotor abilities are the link between cognitive functioning and physical movement (e.g., pressing a button) [39]. They are fundamental to assessing higher-order cognitive functions such as short-term memory [40]. Four studies included eight measures of basic psychomotor abilities [41-44]. Methods and results of these studies were inconsistent across studies. Solianik and colleagues [41] were the only researchers to specifically examine psychomotor and fine-motor control using a finger-tapping (pressing a button as many times as possible in 10 seconds) and pursuit-tracking task (tracking an object on a computer screen using a computer mouse). The fasted and control conditions did not significantly differ in performance on these tasks. Results of reaction time (RT) tasks provide no clearer insight into the modulation of psychomotor abilities when fasting. Cherif and colleagues [42] found the control group to be significantly faster in simple RT than the fasted group, whereas Ginieis and colleagues [43] observed those who drank glucose were slower than other conditions regardless of fasting. Of the three studies that used two-choice [41], four-choice [44], or “complex” [42] RT tasks, only Solianik and colleagues [41] observed a significant difference between groups, with the control group performing better than the fasted group. Results from studies in our previous review [22] were similarly mixed: two studies resulted in the fasted condition performed worse, two reported the inverse, and four showed no significant differences between conditions. Therefore, whether, and how, psychomotor abilities are impacted by fasting remains unresolved.

Processing Speed

Processing speed refers to the amount of time it takes to respond to new information from the environment. Like psychomotor speed, it is fundamental to assessing higher order functioning. One study [35] evaluated processing speed using a Symbol Digit Coding task. Performance between fasted and control conditions did not significantly differ. Ginieis and colleagues [43] asked participants to rapidly confirm if a simple arithmetic equation was correct, with results indicating that the fasted condition completed these problems slower than the control condition (accuracy was not reported). We previously [22] identified one study [45] that found a significant decrement of RT on the task, but the results were complex and varied as a function of time of day and task difficulty. Thus, despite processing speed being a critical component of most of the cognitive tasks included in these studies, only two directly tested if it is impacted by fasting and the results are unclear.

Task Engagement

Task engagement is the ability to maintain cognitive activation to task completion. It is typically measured with RT and accuracy of extended durations of simple tasks. Zajac and colleagues [46] modified a serial subtraction task wherein participants counted backwards from a random number between 800 and 999 by 3 and then again by 7. Typically, this task is brief and measures working memory and attention, but the authors extended the task to two minutes each block. They did not observe a significant difference between conditions. This contrasts with two results (within one study) from our previous review [22] that found significant impairment in the fasted condition compared to unfasted conditions in similar tasks [47]. No other studies directly measured task engagement. More work is needed to establish if concentration and task engagement are altered by fasting.

Perceptual Abilities

Seven studies within five articles [41, 48-51] included measures of visual perception, or the ability to process and respond to visual stimuli. No studies involving this domain were identified in our previous review [22]. Pender and colleagues [48] observed that participants completed the Group Embedded Figures Task faster and more accurately when fasted. Zitron-Emanuel and Ganel [50] observed a significant decrement in object size discrimination of neutral stimuli (i.e., Just Noticeable Difference scores) when fasted using a within-subjects design that included men in the sample (Experiment 2) but not using a between-subjects design with only women (Experiment 1). The remaining studies did not observe significant differences between fasted and control conditions when estimating the size of neutral objects. Together, these results provide little support of an effect of fasting on visual perception of neutral objects. Just three labs conducted the seven studies in this review, and only two studies [50, Experiment 2; 51, Experiment 2] included men in the sample ([50] was the only sample to show a significant decrement when fasted). Greater diversity of researchers and research participants is needed to confirm whether fasting impacts visual perception and if perception is limited to food-related stimuli.

Memory

Contemporary models of memory include three overarching components: short-term memory (STM), working memory (WM), and long-term memory (LTM) [52]. STM is a limited capacity system that maintains simple information up to several seconds, whereas information in WM is simultaneously processed or manipulated for goal pursuit [53]. Although WM is considered an executive function [54], it is presented here for simplicity. LTM refers to storage of information for minutes or more [52]. In our previous review [22], memory was the most frequently studied domain, with wide-ranging assessments in verbal and visual STM, WM, and LTM. In contrast, in the present review, just three studies within two articles probed STM [38, 41], five studies within four articles examined WM [35, 36, 44, 46], and none measured LTM. Consistent with our previous review [22], these domains were generally unimpacted by fasting status. In the two paragraphs that follow, we present a more fine-grained summary of these results.

Short-term memory. In two tasks, Macpherson and colleagues [38] asked participants to memorize a list of words without (Recognition Memory Task) and with (Dual Recognition Task) distraction. Older, but not younger, adults who were fasted and drank a glucose beverage performed better than the control group in both tasks. Solianik [41] did not find differences between fasting and control conditions. No study in this review examined non-verbal STM. Together with our previous review [22], the ability to recall lists of neutral verbal information is seemingly unimpacted by fasting.

Working memory. Komiyama and colleagues [55] found participants performed better in the control condition than the fasted condition on a visuospatial WM task in which participants reported the location of a stimulus presented on screen after distractors. None of the remaining studies [35, 36, 44] found that fasting significantly impacted verbal WM. Like STM, there is seemingly little or no impact of fasting on verbal and visual WM across studies.

Executive Functioning

Executive functioning (EF) comprises several higher order processes including attention, inhibition, and cognitive flexibility [54]. Of the 21 studies included in this review, most (n = 16; 76%) presented results from at least one measure of EF for a total of 22 comparisons between fasted and unfasted conditions. Fifteen of these 22 (68%) showed a significant impact of fasting of which 14 (93%) showed a decrement in performance. Across studies, the domains within EF were the most consistently impaired during fasting. However, the pattern of observed results is complex. For example, some results showed deficits only in RT [43, 56], some showed decrements only in accuracy [57], some showed both [42], and some showed neither [58]. Some studies showed deficits presented at the onset of testing [35] whereas with others the difference emerged over time [36, 59]. Taken together, emerging evidence suggests EF is vulnerable to negative effects of caloric restriction, though the results should be interpreted cautiously.

Attention/Inhibitory Control. Inhibitory control is the ability to suppress irrelevant or incompatible stimuli and behavioral responses for goal pursuit [54]. Attentional and inhibitory control were measured using Go/NoGo (GNG) and Continuous Performance Tasks (CPT). GNG indexes behavioral inhibition whereas CPT indexes an ability to maintain vigilance [54, 60]. Nearly all studies that included measures of attentional control and inhibition showed a decrement as a function of fasting, though this pattern is qualified by several interactions with timing, dependent variable (accuracy vs. RT), and control group. For example, two studies using a GNG found reduced behavioral accuracy when fasted [36, 55] and one identified slower reaction time [41]. However, Anderson and colleagues [36] only found a difference 120 minutes after milk ingestion compared to a water ingestion. Anderson and colleagues [35] found that participants performed better on a CPT immediately after drinking juice than water, but not later in the experiment. Kumar and colleagues [59] found that those who drank water exhibited a decline in CPT performance over 20 minutes whereas those who ingested a carbohydrate drink exhibited consistent performance. In an Affective Shifting Task, Howard and colleagues [37] found that the control condition made fewer errors of commission but made greater errors of omission than the fasted condition. Bartholdy and colleagues [58] found no differences in two measures of inhibitory control.

***Selective Attention*.** Selective attention, a type of cognitive control [54], is defined as the ability to attend to a target and ignore a distractor [61], such as in the Stroop [62] task. Three studies found an impact of fasting on performance, whereby two found the control group to respond faster in the task [35, 56], suggesting less difficulty ignoring distraction, whereas Ginieis et al. [43] found the opposite. Two studies did not find significant differences between fasted and unfasted groups [44, 57]. No study observed differences in accuracy on the task. Similarly, our previous review [22] found no study that identified a significant impact of fasting on Stroop accuracy, though two studies reported a trend-level decrement in reaction time associated with fasting [45, 63]. It remains unclear whether, and how, fasting impacts selective attention.

***Cognitive Flexibility*.** Cognitive flexibility can be understood as the ability to switch tasks, adapt to changes in rules, or overcome obstacles within a task [64]. Four articles reported results of five measures of cognitive flexibility [35, 48, 57, 65]. Fasting was associated with a significant impact on cognitive flexibility in four of the five measures. Based on the descriptive statistics presented by Riby and colleagues [57], fasted participants committed significantly more errors overall than did participants who ingested a glucose drink. Pender and colleagues [48] and Bolton and colleagues [65] conducted a Rule Change Task in which participants rapidly decided whether the total number of pictures presented on screen were odd/even or high/low in randomized order. In both studies, fasting participants had slower responses immediately following a rule change. Pender and colleagues [48] also used a Local-Global Task in which participants judged whether an array of shapes formed a target letter (i.e., the “global” condition) or if the individual shapes in an array were the target letter (i.e., the “local” condition). Participants in the fasted condition exhibited a significant bias to local processing and impairment in processing global stimuli, especially under switch conditions. The remaining study found no significant group differences in cognitive flexibility [35]. These results, together with our previous sample of studies [22], provide generally consistent evidence of impaired cognitive flexibility when fasted. This conclusion is qualified by acknowledging that three of the five included measures of cognitive flexibility were conducted by the same research group. Additional work from a greater number of labs is needed to confirm these results.

***Planning*.** Two studies [37, 42] assessed planning and problem solving with tasks that do not fit cleanly into other measures of EF. Participants in Cherif and colleagues [42] completed the One Touch Stockings of Cambridge task in which they guessed the minimum number of moves needed to solve a puzzle. Participants in the control condition were faster and more accurate than when fasted. Howard and colleagues [37] adminstered the Information Sampling Task, wherein participants were presented 25 gray boxes in a 5 x 5 grid and selected one at a time to reveal each box's color until they could guess which color is in the majority. They completed the task during conditions of higher or lower stakes. The results indicate that participants in the control condition were *less* accurate overall but clicked on significantly fewer boxes in the lower stakes condition, whereas the two groups did not significantly differ in the higher stakes condition. The authors suggested that fasting increased perseveration and reduced tolerance of uncertainty. There were no analogous planning tasks in our previous review [22]. Together, these results suggest that fasting impairs planning and risk taking in subtle ways that merit further exploration.

Multitasking. The tasks used by Scholey and colleagues [56] were completed simultaneously in a four-way split screen. Thus, their procedure provided scores on the tasks themselves and an overall index of an ability to "multitask," though it could also be construed as a measure of cognitive flexibility. Participants who drank caffeine with glucose performed better than those who drank placebo or glucose only.

Discussion

Longer-term fasting, including intermittent fasting, is increasingly prevalent, and interest in its impact on cognition is similarly growing. With a wide array of research methodologies in this area, a systematic review is warranted to synthesize and interpret the state of the literature. Using similar methodology to our prior systematic review [22], we found almost double the quantity of pertinent studies than we did previously. No studies addressed the impact of longer-term fasting on cognition, which is a critical gap in the literature. Until these studies are available, identifying the impact of short-term fasting on cognition can lend insight into which aspects of cognition may be susceptible to changes from longer-term fasting. As with our prior review, the studies we found were heterogeneous, with sample sizes ranging from 10-150 participants, the majority of whom were women. Average fasting time varied dramatically between studies, as did the instructions for fasting (and control conditions). The results of these studies provide limited consistent results.

Basic cognitive processes (psychomotor abilities, memory function, and processing speed) are critical components of other cognitive domains and higher-order functions, yet whether, and how, they are impacted by fasting remains relatively understudied. Intuitively, reduced energy availability would impact these basic processes. However, consistent with our previous conclusion [22], the relative dearth of published studies examining basic cognitive and psychomotor domains (and the heterogeneity of methodology found in this area) makes it nearly impossible to fully understand the impact of fasting on basic cognition. It remains unclear if, or how, modulations in higher-order functions (e.g., executive functioning) can be explained by deficits in basic processes such as reaction time and processing speed.

Although WM was frequently assessed in studies included in our prior review, most studies in this review assessed EF beyond WM. Across domains of attention, selective attention, and cognitive flexibility, participants exhibited detriments as a function of fasting, with cognitive flexibility showing the most consistent impairment. This trend may provide insight into eating pathology. There is a consistent observation that adults with active eating disorders exhibit impairments in cognitive flexibility. Like those who were fasted in this review, those impairments persist following recovery [66]. Thus, the pattern of results here supports the postulation that inefficiencies in cognitive flexibility in adults recovered from anorexia [67, 68] may be a scar from long term caloric restriction or may have been premorbid and worsened following protracted starvation. More work is needed to understand the short and long-term impact of caloric restriction, both in the context of an eating disorder and in the context of otherwise healthy individuals who engage in regular or intermittent fasting.

Despite increasing interest in fasting on cognition, the literature continues to be plagued by basic methodological flaws and inconsistencies making it difficult to draw conclusions about the impact of fasting on cognitive functioning. Overall, studies included in this review suffered from lack of power, insufficient description of fasting and control methodology, insufficient description of tasks used, and a relative neglect of simpler cognitive processes. Generalizability is also limited as most of the participants included in these studies were overwhelmingly young, female undergraduates from Western, high-income cultures. No studies reported the racial or ethnic composition of their samples. Greater diversity of study design and samples is needed to draw conclusions about validity.

Conclusions

Even with these methodological shortcomings and inconsistencies and conflicting findings, a pattern is emerging that fasting for 3-48 hours is more likely to be associated with impairment in higher-order functions (e.g., attention, inhibitory control, flexibility, and planning) than simpler functions such as RT and memory. However, these more basic functions are relatively unexamined. Diminished EF may have the potential to affect performance of complex tasks in the workplace, while driving or commuting, or when making financial, legal, or other important personal decisions. Given the increased prevalence of fasting [27], it is vital to fully understand how the practice impacts cognition and behavior, who is more likely to be affected, and what duration and pattern of fasting can diminish functioning. Intermittent fasting is suggested to have significant physiological benefits, yet the risks to cognition remain unclear and further research is needed before potential risks can be fully understood.

As research into the impact of fasting continues, the results of this review highlight areas that need to be considered and reported to increase replicability [69]. It is essential that justification of sample size be presented [70]. Full instructions for fasting protocols need to be clearly described, including fasting duration, time of day of task completion, limitations on water consumption, caffeine and tobacco use, and exercise prior to the experiment. Experimenters should also note participant sleep quantity, medication, and timing and details of food consumed in the control condition. BMI should also be assessed to determine whether effects differ across underweight, healthy, and overweight individuals. Description of demographic composition of samples is needed, as is greater diversity to increase validity and determine generalizability of effects, including gender, socioeconomic status, nationality, race, and ethnicity [71].

Although this review provides insight into whether, and how, fasting influences cognition, there are certain limitations that should be noted. We limited the scope of this review to published peer-reviewed studies that included only healthy adults, behavioral tasks that indexed cognition and information processing, and excluded religious fasting and neuroimaging data. We did not exclude studies based on water consumption, which is a possible confounding variable in tests of cognition [72]. We also omitted tasks related to reward processing, monetary value, or that included food-related stimuli exclusively. We also did not find any studies examining longer-term intermittent fasting (e.g., for several days or more) outside of religious observation (e.g., comparing fasters and non-fasters). Each of these are important considerations for future analysis that can provide further insight into the wide-ranging impacts of fasting on mental processes in different contexts across the lifespan. Finally, descriptive statistics were not always available in the included articles, which impacted our ability to verify the findings or directly assess fasted vs. control groups when these analyses were not available. When these data were not available, we relied on narrative descriptions provided by the authors to make conclusions about fasting and cognition. Thus, there may be findings that are discrepant from the published articles presented in this review.

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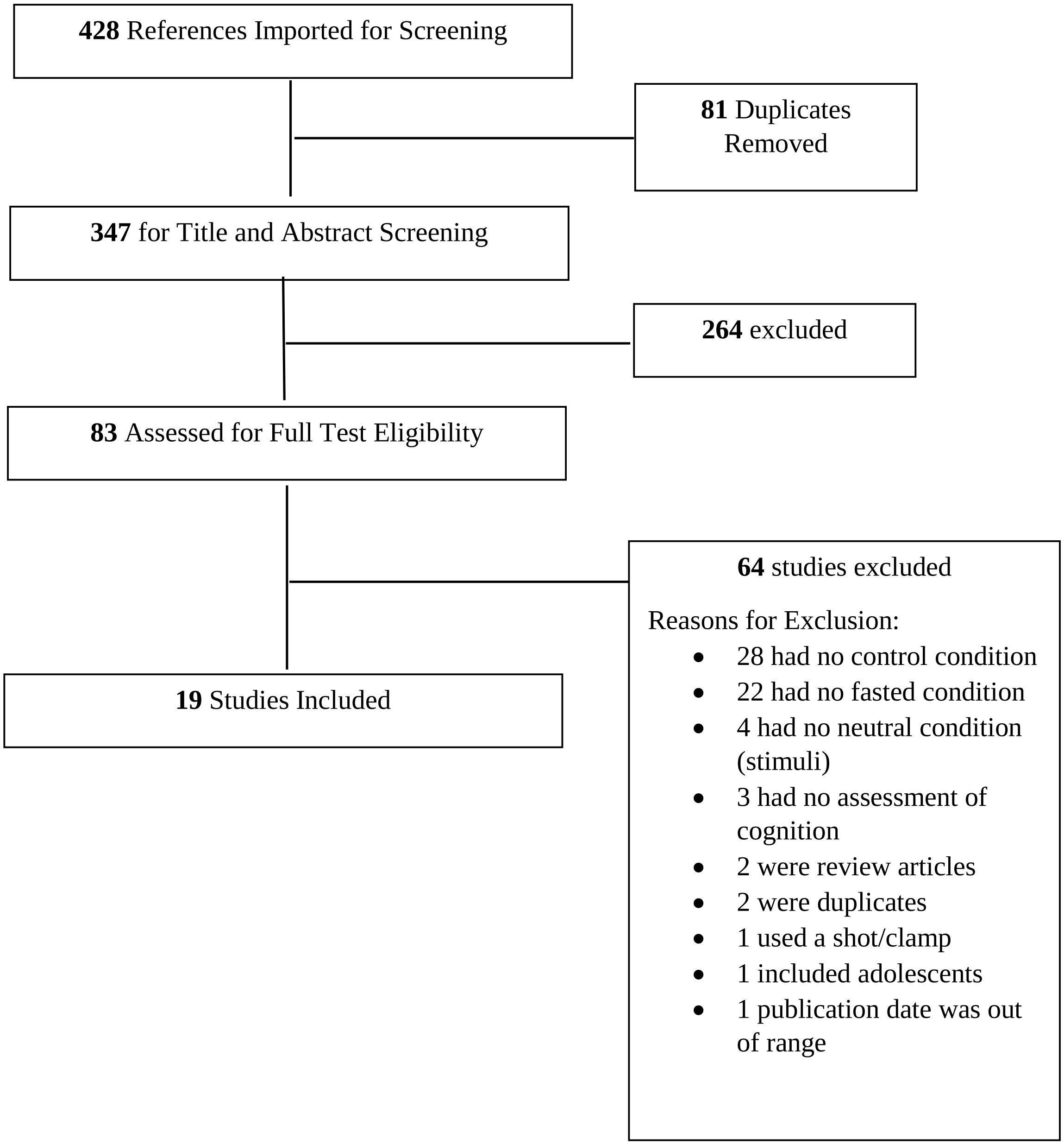

Figure 1. PRISMA flow diagram detailing the number of articles identified, abstracts screened, and full text articles reviewed.

Table 1. Description of studies included in the current review

First Author (year) [Reference]	Country	Design	Total N	% Female	BMI	Age (years)	Time Fasted	Fasting Description	Control Notes	Design Notes
Anderson (2018) [36]	United States	Within	86	57	M = 29.24 SD = 8.05	M = 21.09 SD = 2.48	8-12h Overnight		8 oz of milk or apple juice prior to each session	Given water during experiment
Anderson (2020) [35]	United States	Within	44	50	M = 26.50 SD = 4.63	M = 30.81 SD = 8.36 Range: 18–49	8–12h Overnight		237 mL of milk or apple juice consumed prior to each session	Given water during experiment
Bartholdy[a] (2016) [58]	United Kingdom	Within	46 (31 in proactive inhibition task)	85 (81% in proactive inhibition task)	M = 21.60 SD = 1.69	M = 24.90 SD = 6.62 Range: 18–49	Overnight	Permitted to drink water during fast	Consumed "normal breakfast"	
Bolton (2014) [65]	United Kingdom	Within	60[f]	100	M = 22.3 SD = 2.9 Range: 17.8–29.3	M = 27.4 SD = 7.41 Range: 19–55	M: 16.67h Range: 15.2 – 21h	Permitted to drink water during fast	Consumed "regular meals"	
Cherif (2017) [42]	Qatar	Within	21	0	Not reported	M = 29.8 SD = 5.9	14h from dawn to sunset	Abstain from eating or drinking	Last meal 5 h before experiment and no drink allowed during experiment	Fasting modeled after third consecutive day of IF; testing took place after sunset

Ginieis (2018) [43]	New Zealand	Between	49 (53% fasted)	Fasted group: 58 Fed group: 57	Whole sample: Range: 17.6–32.7 Fasted group M = 23.2 SD = 3.56 Fed group M = 24.1 SD = 3.87	Fasted group: M = 22.6 SD = 4.2 Fed group: M = 24.3 SD = 4.9	10h	Given 0kcal placebo (sucralose) during experiment	Reported the caloric content of their most recent meal. (Avg = 271 kcal, 55g carbohydrate). Given glucose, fructose, sucrose drink during experiment	
Howard (2020) [37]	United Kingdom	Within	33[f]	100	M = 21.65 SD = 3.22	M = 25.42 SD = 8.26	20h	Not reported	Not reported	
Komiyama (2016) [55]	Japan	Within	10	0	M = 24.4 SD = 2.0	M = 22.3 SD = 2.1	14h	Last meal at 7pm the evening before experiment	Standardized consumption of two rice balls and water	Given water during experiment
Kumar (2016) [59] Study B [b]	United States	Within	10[f]	60	M = 24.5 SD = 2.6	M = 28.3 SD = 6.7	Overnight	Consumed control solution (0% CHO)	Consumed 0.4%, 0.75%, 01.5%, or 6% carbohydrate (CHO) drink.	
Macpherson (2015) [38]	Australia	Between	Younger group: 24 Older group: 24	Younger group: 63 Older group: 46	Younger group: M = 24.6 SD = 4.0 Older group: M = 28.4 SD = 4.3	Younger group: M = 20.6 SD = 1.4 Older group: M = 72.5 SD = 5.1	12h Overnight	Permitted to drink water during fast	Consumed solution containing 75g glucose	Given placebo drink during experiment
Pender (2014) [48]	United Kingdom	Within	60[f]	100	M = 22.3 SD = 3.8 Range: 16.4 - 32.2	M = 23.2 SD = 3.8 Range: 18–30	18h	Permitted to drink water during fast	Not reported	

Riby (2017) [57] [c]	United Kingdom	Between	Study 1: 60[f] Study 2: 40[f]	Study 1: 63 Study 2: 68	Not reported	Study 1: M = 20.7 SD = 1.5 Study 2: M = 20.3 SD = 1.4	Study 1: 3h Study 2: 2h	Total abstention from food and drinks	Consumed 15 g of glucose dissolved in 200 mL water	Completed task 30 minutes after consuming glucose drink
Scholey (2014) [56]	United Kingdom	Between	150[f] 37 (25%) in placebo group 38 (25%) in 25g glucose group 39 (26%) in 60g glucose group 36 (24%) in 60g glucose+40 mg caffeine group	All participants: 65 Placebo: 68 25g Glucose: 55 60g Glucose: 64 Caffeine+ glucose: 58	Total: M = 24.36 SD = 4.45 Placebo group: M = 24.70 SD: 4.05 25g Glucose group: M = 24.10 SD = 5.22 60g Glucose group: M = 23.97 SD = 3.65 Caffeine+ glucose group: M = 24.72 SD = 4.86	Total: M = 34.78 SD = 10.63 Placebo group: M = 34.78 SD: 10.00 25g Glucose group: M = 31.85 SD = 11.02 60g Glucose group: M = 31.44 SD = 10.32 Caffeine+ glucose group: M = 34.78 SD = 11.09	12h	Given placebo drink prior to task completion	Consumed 25g glucose, 60g glucose condition, or 60g glucose+40mg caffeine	
Solianik (2020) [41]	Lithuania	Within	11	100	Usual diet group: M = 31.8 SD = 4.4 Fasting group: M = 32.5 SD = 4.6	M = 68.8 SD = 6.4 Range: 63–80	48h	Permitted to drink water during fast	Usual diet	BMI refers to pre-intervention

Veasey (2013) [44]	United Kingdom	Within	12	0	M = 24.5 SD = 2.0	M = 23.2 SD = 2.4	12h	Not reported	Standardized meal (breakfast)	Data refer to pre-exercise segment
Zajac (2021) [46]	Australia	Within	17[f]	100	M = 25.8 SD = 2.30	M = 31.94 SD = 2.30 Range: 21–49	Not reported	Total abstention from caloric items	Standardized meal	
Zitron-Emanuel (2018a) [50] Exp. 1 [d]	Israel	Between	67 (54% fasted)	100	Not reported	M = 22.98 SD = 1.53 Range: 18–29	≥ 3h	Total abstention from food	Eat within 1 hour of experiment ad libitum	
Zitron-Emanuel (2018a) [50] Exp. 2 [d]	Israel	Within	27	51	Not reported	M = 23.36 SD = 2.35 Range: 18-31	≥ 3h	Total abstention from food	Eat within 1 hour of experiment ad libitum	
Zitron-Emanuel (2018b) [51] Exp. 1 [d]	Israel	Within	28	100	Not reported	M = 24.31 SD = 2.00 Range: 20–30	≥ 3h	Total abstention from food	Eat within 1 hour of experiment ad libitum	
Zitron-Emanuel (2018b) [51] Exp. 2 [d]	Israel	Within	68	49	Not reported	M = 19-29 SD = 1.79 Range: 19–29	≥ 3h	Total abstention from food	Eat within 1 hour of experiment ad libitum	
Zitron-Emanuel (2020) [49] Exp. 2 [d,e]	Israel	Within	40	100	Not reported	M = 23.9 SD = 1.6 Range: 22–27	≥ 3h	Total abstention from food	Eat within 1 hour of experiment ad libitum	

Notes: All available data regarding fasting duration, control conditions, body mass index (BMI) and age composition are presented here; decimals are rounded as original authors presented them; metric, US Customary, or imperial units are as original authors presented them; IF = intermittent fasting; LMR= liquid meal replacement; SRB= snack replacement bars;

[a] Authors report data loss in the Proactive Inhibition task, but do not provide age and gender composition for the included sample

[b] Study A was omitted from this review (no cognitive tasks were completed);

[c] Descriptive statistics were used to analyze behavioral data from Study 1 (fasting) and Study 2 (glucose condition)

[d] Unclear if descriptive data refer to whole sample or those included in final analyses

[e] Experiment 1 was omitted from this review (food-related stimuli presented in all trials)

[f] Power analysis or sample size justification was provided in the article.

Table 2. Results of each study included in the review.

Domain/Measure	First author (year) [reference]	Test	Effect of Fasting?	More accurate	Faster RT	Notes
Psychomotor Ability						
Tapping	Solianik (2020) [41]	Finger-Tapping	No	--	N.S.	
Reaction Time	Cherif (2017) [42]	Simple RT	Yes	N.S.	N.S.	Measured as pressing a dot on a touchscreen in one location.
	Ginieis (2018) [43]	Simple RT	Yes	--	Fasted	RT faster for fasted condition; glucose ingestion slowest in both conditions.
	Veasey (2013) [44]	Simple RT	No	#	#	
	Solianik (2020) [41]	Two-choice reaction time test	Yes	--	Control	
	Cherif (2017) [42]	Complex RT	Yes	Control	N.S.	Measured as pressing a on a touchscreen in one of four locations.
	Veasey (2013) [44]	Four Choice Reaction Time	No	#	#	Pressed arrow buttons corresponding to figure appearing on screen.
Psychomotor Control	Solianik (2020) [41]	Pursuit Tracking Task	No	N.S.	N.S.	
	Ginieis (2018) [43]	Arithmetic	Yes	--	Control	
Concentration/Task Engagement	Zajac (2021) [46]	Serial Subtraction (3s and 7s)	No	#	#	
Processing Speed	Anderson (2020) [^,‡] [35]	Symbol Digit Coding	No	N.S.	N.S.	
Perceptual Abilities	Pender (2014) [48]	GEFT	Yes	Fasted	Fasted	
	Solianik (2020) [41]	Matching Grids	No	N.S.	N.S.	

	Zitron-Emanuel (2018a) † [50] Exp. 1	JND	No	N.S.	--	
	Zitron-Emanuel (2018a) † [50] Exp. 2	JND	Yes	Control	--	
	Zitron-Emanuel (2018b) † [51] Exp. 1	Object Perception Size Task	No	N.S.	--	
	Zitron-Emanuel (2018b) † [51] Exp. 2	Object Perception Size Task	No	N.S.	--	
	Zitron-Emanuel (2020) † [49] Exp. 2	Object size Estimation Task	No	N.S.	--	
Memory						
STM	Macpherson (2015) [38]	Recognition Memory Task	Yes	#	Control	Effect was seen in older, but not younger, adults
	Macpherson (2015) [38]	Dual Recognition Task	Yes	Control	#	Effect was seen in older, but not younger, adults
	Solianik (2020) [41]	Memory Search	No	N.S.	N.S.	
WM	Veasey (2013) [44]	N-Back	No	#	#	
	Veasey (2013) [44]	RVIP	No	#	#	
	Komiyama (2016) ^ [55]	Spatial Delayed Response Task	Yes	Control	--	
	Anderson (2020) ^, ‡ [35]	4PCPT	No	N.S.	--	
	Anderson (2018) ^ [36]	RMCPT	No	N.S.	N.S.	
Executive Functioning						
Attention/Inhibitory Control	Zajac (2021) [46]	Mackworth Clock Test	No	#	#	
	Anderson (2018) ^ [36]	GNG	Yes	Control	N.S.	Milk ingestion condition made fewer errors of omission than water at 120 minutes
	Komiyama (2016) ^ [55]	GNG	Yes	Control	N.S.	Difference seen in "go" trials only

	Solianik (2020) [41]	GNG	Yes	N.S.	Control	Difference seen in "go" trials only
	Anderson (2020) ^, ‡ [35]	CPT	Yes	--	Control	Juice performed better than water only at 0 m following drink
	Kumar (2016) [59] Study B	CPT	Yes	Control	N.S.	Differences emerged only after 20 minutes of task.
	Anderson (2018) ^ [36]	CPT	Yes	Control	N.S.	Juice ingestion condition committed fewer errors of omission than water at 60 minutes
	Bartholdy (2016) ^ [58]	Stop Signal Task	No	N.S.	N.S.	
	Bartholdy (2016) ^ [58]	Proactive Inhibition Task	No	N.S.	N.S.	
	Howard (2020) [37]	Affective Shifting †	Yes	See notes	N.S.	Compared to fasted, control made fewer errors of commission but more errors of omission
Selective Attention	Veasey (2013) [44]	Stroop	No	#	#	
	Riby § (2017) [57]	Stroop	No	N.S.	N.S.	
	Scholey (2014) [56]	Stroop	Yes	N.S.	Control	Placebo slower than caffeine + glucose
	Ginieis (2018) [43]	Stroop	Yes	N.S.	Fasted	Glucose and sucrose were faster than other conditions.
	Anderson (2020) [35]	Stroop ¶	Yes	N.S.	Control	Milk condition was significantly faster than water only at 150 minutes.
	Zajac (2021) [46]	Color Multi-Source Interference Test	No	#	#	
Cognitive Flexibility	Anderson (2020) ^, ‡ [35]	Shifting Attention Task	No	N.S.	N.S.	Juice performed better than water at 90 m following drink at a trend (p = .081)
	Riby (2017) § [57]	WCST	Yes	Control	--	
	Pender (2014) [48]	Local-Global Task	Yes	See Notes	--	Fasting > Local Processing than Global Processing; Control showed inverse

	Pender (2014) [48]	Rule Change Task	Yes	N.S.	See Notes	Fasted were faster overall, however they showed greater impairment than control when shifting rules
	Bolton (2014) [65]	Rule Change Task†	Yes	Control	See notes	Fasted were faster overall, however they showed greater impairment than control when shifting rules
Planning	Cherif (2017)^ [42]	One Touch Stockings	Yes	Control	Control	Control performed better in nearly all parts of this task
	Howard (2020) [37]	Information Sampling	Yes	Control	--	Control opened more boxes than fasted before final decision (i.e., less impulsive)
Misc.						
Multi-Tasking	Scholey (2014) [56]	Multi-Tasking Framework Task*	Yes	See notes	N.S.	Glucose + caffeine group more accurate than placebo and 60 g glucose

Notes: All results presented here reflect responses to neutral stimuli only; in cases with food or emotional stimuli, we conducted analyses using available descriptive data or data provided by authors when available; N.S. = not significant; RT = reaction time; GEFT = Group Embedded Figures Task; RVIP = Rapid Visual Information Processing task; CPT = Continuous Performance Task; GNG = Go/NoGo task; 4PCPT = Four Part CPT; RMCPT = Running Memory CPT; JND = just noticeable difference; WCST = Wisconsin Card Sorting Task

† Food-related stimuli used, but neutral stimuli analyzed separately and/or there was no effect of food-relatedness and all combined;

‡ Results are based on difference scores [correct - error];

^ Results presented here are based on our analyses of descriptive statistics and may not reflect what is presented in original article;

¶ Data were provided to our team by study's authors and are not presented in published manuscript;

Authors reported relevant main effects and interactions of fasting/fasting type were not significant, but did not provide descriptive or inferential statistics to confirm;

* four separate tasks engaged in simultaneously (Stroop, mental math (working memory), memory recall, target tracker (attention/RT);

§ Data presented were analyzed by the present authors comparing Study 1 and Study 2;

-- data not presented, collected, or available