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Pupillary Effects During Retrieval: Influenced by Cognitive Load and Strength of Memory

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PUPILLARY EFFECTS DURING RETRIEVAL:
INFLUENCED BY COGNITIVE LOAD AND STRENGTH OF MEMORY

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ABSTRACT

Memory retrieval is influenced by cognitive processes that occur during encoding, some of which can be measured with pupillary responses. For example, during retrieval, pupils dilate more to previously-seen old items compared to new items, a phenomenon called the pupil old/new effect. Encoding variables that influence the strength of the memory trace for encoded stimuli play a role in successful discrimination of new versus old items. Additionally, the cognitive load during encoding (i.e., the effort needed to encode information), also impacts memory success by taking up mental resources needed to successfully encode information. In this study, I conducted a meta-analysis to examine whether pupillary dilation effects are stronger after encoding manipulations that influence memory strength or cognitive load. This analysis showed that both memory strength and cognitive load affect pupil dilations. However, the impact was greater for cognitive load, suggesting that the amount of effort required to process information during encoding has a greater impact on pupil size than variables that affect the strength of the memory trace. Pupillometry can be a useful measure of memory effects, so future research could use pupil measures to study variables that affect other types of memory, such as explicit versus implicit memory.

I dedicate this thesis to my family, who have been the greatest support system I could have ever asked for.

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VITA

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SECTION ONE

Pupillary Responses and Mechanisms

When leaving a movie theater, most people will squint their eyes as their pupils adjust to the light. It is common knowledge that pupils dilate and constrict in response to environmental light. This is the pupillary light reflex controlled by innervations in the central nervous system, a response to external light entering the eyes in virtually every sighted individual (Szabadi, 2012). However, pupils can also dilate based on the context and interest in stimuli in the visual field, such as when looking at an adorable puppy, a significant other, or a complex phrase. This is the psychosensory pupil response, a product of changes in cognitive activity and mental effort in cognitive and sensory systems (Mathôt, 2018). Pupil dilations themselves are driven by the sympathetic system, which is controlled by a neuromodulatory brain system called the locus-coeruleus, norepinephrine (LC-NE) system (van der Wel & van Steenbergen, 2018). Activation of the LC-NE system reflects behavioral changes in alertness demonstrated by quick changes in pupil diameter (Gabay, Pertzov, & Henik, 2011). The release of norepinephrine from the locus coeruleus helps to guide cognitive processes such as memory in the cortex (Hoffing & Seitz, 2015), which can be seen in many studies examining the relationship between pupil dilations and memory.

When the pupils dilate for reasons other than external sensory influences, such as cognitive processes, pupillometry is an efficient way to measure these responses—eyes, in essence, are windows into the brain. Eye-trackers have been used for studying pupillometry within the last few decades, and this method has gained increasing popularity in psychophysiological research (Laeng, Sirois, & Gredebäck, 2012). This is a relatively inexpensive and non-invasive way to measure brain activity and subsequent physiological reactions. According to Laeng et al. (2012), pupillometry can be used to track preconscious states, during which information processing is occurring before the individual has a conscious perception of the information, by measuring minute pupillary responses. In addition, pupils seem to be reliable reflections of the cognitive activity occurring in the brain during conscious awareness and processing.

The Pupil Old/New Effect

Pupil dilation is influenced by cognitive processes such as memory encoding and retrieval. A common way of studying memory is to have participants make old/new judgments during a recognition task. During recognition, participants must judge at test whether the stimuli presented have been presented during study or are newly presented during testing. Using event-related potentials (ERPs), Wang, Du, and Ma (2017) found that correctly judging old items elicits greater, more positive ERPs than judging new items. Research has also shown a phenomenon similar to the ERP old/new effect in pupil dilation patterns. Specifically, pupils dilate more at test to items correctly judged as old compared to new. Võ et al. (2008) coined the term the 'pupil old/new effect' to describe this relationship between pupil dilations and old/new judgments. This pupillary pattern may reflect the heightened arousal levels in the brain when viewing previously-seen items, especially to items that have an emotional valence (Võ et al., 2008). Interestingly, Heaver and Hutton (2011) found this pupil old/new effect under a standard memory condition, a malingering condition in which participants were instructed to forget, and a single-response condition in which all items regardless of their actual old/new status were instructed to be judged as new at test. This robust effect gives insight into the neural connections between pupillary responses and retrieval.

The pupil old/new effect is influenced by a range of mental processes including those that reflect encoding for future memory tests. Manipulations such as encoding real versus pseudowords, positive versus negative words, and low-frequency versus high frequency words affect the pupil old/new effect words (Brocher & Graf, 2016). Brocher and Graf suggest that the fact that pupils will dilate more for ‘remember’ rather than ‘know’ responses indicates that the pupils can discriminate between responses made on the basis of recollection and familiarity that are associated with one’s subjective feelings. They found robust effects of the pupil old/new effect in five experiments assessing the strength of memory traces with judgments of familiarity and recollection. Their findings suggest that the pupil old/new effect reflects subjective feelings or possibly more general aspects of memory traces such as aggregate strength. Their results indicated that when participants are given sufficient resources to encode stimuli and create representations in their short-term memory, the pupil old/new effect is positively associated with memory strength. These cognitive influences on observed pupillary patterns are the main focus of this meta-analysis.

Cogntitive Influences on Pupil Dilation during Retrieval

Different cognitive constructs affect memory. It is well-known that as time passes, one’s memory fades and the strength of memory traces deteriorates. The strength of the memory traces has a strong impact on pupillary responses. Memory strength can be studied in a myriad of ways. For example, autobiographical memories tend to be strong memories. In a study by Haj, Janssen, Gallouj, and Lenoble (2019), participants had to recall three autobiographical events: one free memory, one positive memory, and one negative memory, and perform a separate control counting condition, while their pupil dilations were measured. The pupillary measures were significantly greater during the recall of autobiographical events compared to the counting condition, indicating that these memories elicit greater dilations than routine counting. One explanation for this is that the locus coeruleus-norepinephrine system in the brain becomes more aroused for self-related memories, especially if there is an emotional component, causing a greater reflex in the pupils. Oliva and Anikin (2018) note that pupil dilations reflect and can predict the emotionality of stimuli by dilating more to negative and positive emotional states compared to neutral states. A study by Bradley and Lang (2015) also demonstrated that emotionality influences pupil dilations and subsequent memory. However, in both studies, the specific emotional valence, violent versus erotic images, of the memory did not significantly affect pupil dilation.

Strength of memory can also be examined by manipulating levels of processing in which deeper levels of encoding and heightened arousal mediate working memory maintenance and pupil dilations for later retrieval (Rose, Craik, & Buchsbaum, 2015). In addition, memory strength can be studied eliciting feelings of subjective confidence. According to Goldinger and Papesh (2012), confidence in one's recall plays role in the pupillary reflex; i. e., the stronger the memory trace for old items, the greater the subjective confidence, and the greater the pupil dilation. It is interesting to note that in individuals with amnesia who have low memory strength and confidence, pupillary effects show an opposite pattern, dilating more to novel items than to old (Laeng et al., 2007). Subjective memory strength is reflected by these neurophysiological reactions, providing insight into the relationship between encoding and the confidence with which people can accurately remember information.

Successful memory can also be influenced by cognitive load, explained by the cognitive load theory (CLT). CLT states that working memory capacity is impacted by the amount of cognitive load, or the amount of information taken in relative to the amount of available resources available in working memory (Paas & van Merriënboer, 2020). Dilations can be seen as a reflex of increasing load. Interestingly, the effects of cognitive load are so influential that Mitre-Hernandez et al. (2018) found that pupils are larger in individuals when they tell spontaneous lies compared to telling the truth because generating lies demand more cognitive resources than telling the truth. Many studies, including a seminal study by Kahneman and Beatty (1966), have shown the indisputable relationship between cognitive load and pupil size.

The cognitive load imposed on someone impacts successful working memory, as resources are limited. For example, Peysakhovich, Dehais, and Causse (2015) found that under high load conditions in which participants are simultaneously under a visual and auditory load in a piloting task, working memory is poorer, making the task difficult to perform and increasing pupil dilations. Again, an explanation to this could be the increasing amount of load increases the arousal of the locus coeruleus-norepinephrine system. However, Wiese and Daum (2006) determined that recognizing a stimulus as old is not more or less cognitively demanding than recognizing a stimulus as new. Thus, the neurocognitive processes driving the relationship between cognitive load and memory strength remain unclear.

The Current Study

Pupil responses are clearly impacted by variables that affect memory retrieval, but there is currently no consensus on whether cognitive load or strength of memory traces has a bigger impact on these pupillary patterns, and what the relationship between these two might be. Because pupillometry has only been employed over the latter half of the twentieth century forward, no studies to date have compared the influences of both cognitive load and memory strength on pupillary responses during retrieval using pupil dilation measures. This meta-analysis compared the effects of these variables on pupil dilation effects during memory retrieval. Specifically, it focused on manipulations at encoding that affect cognitive load and the strength of the memory traces and compared the mean effect sizes to see which had a larger effect.

SECTION TWO: METHOD

Literature Search

Previous studies have demonstrated that manipulations of cognitive load and the strength of the memory trace both influence pupillary responses during retrieval. To obtain studies for this meta-analysis, I began by using electronic searches on EBSCOhost. I used key terms such as “pupil old/new effect”, “cognitive load theory”, “memory strength”, “pupillary responses”, and “memory retrieval” and focused on studies that use recognition or recall to study memory retrieval and measured pupil dilations during these tests. The criteria for inclusion were that the study must have been peer-reviewed, published from 1960 and forward, and conducted either in the United States or western European countries. In addition, the study must have examined memory retrieval after experimental manipulations of cognitive load or strength of memory during encoding. All of the studies selected used modern eye-trackers with the exception of an older study that used camera picturers to take snapshots of the pupils. The studies selected for the meta-analysis are described in Tables 1 and 2.

Manipulations of Cognitve Load

Five studies were obtained that manipulated cognitive load during encoding and measured subsequent pupillary measures during retrieval. The first was the classic study conducted by Kahneman and Beatty (1966) in which cognitive load was manipulated prior to short-term memory recall. In their within-subjects design, five participants encoded sequences of digits of different lengths, nouns of high or low frequency, and transformed digits followed by immediate recall. Pupils were measured by taking five pictures of pupils before the presentation of the sequences, and four pictures during recall. Peak pupillary diameters were obtained and analyzed. In the second study (Klinger, Tversky, & Hanrahan, 2011), digit sequence length was also manipulated. For this analysis, only experiment two of Klinger et al. (2011) was used. This experiment was a replication of the Kahneman and Beatty (1966) within-subjects study, but they presented the sequences of digits either aurally or visually to the 24 participants and used a modern eye-tracker.

The third study by Pajkossy and Racsmany (2019) used a within-subjects design and manipulated word-pair set size during a paired-associates learning tasks. The 38 participants studied paired-associates and used the cue word to recall the target word at test while the eye-tracker measured both early pupil response (0-1000msec after stimulus presentation) and late pupil response (1000-5000msec after presentation) during retrieval. The fourth study by Piquado, Isaacowitz, and Wingfield (2010) compared younger and older adults' recall after manipulations of digit list length, sentence length, and syntactic complexity. The researchers conducted two separate experiments, both with mixed designs. In the first, digit list length was manipulated using 15 young adult and 15 older adult participants, and in the second, sentence length and syntactic complexity was manipulated using 18 younger and 18 older adults. Participants were asked to verbally recall in the correct order as many digits and sentences as they could. The fifth and final study obtained for the cognitive load category was by Van Gerven, Paas, van Merriënboer, and Schmidt (2004) in which memory set size was manipulated in a Sternberg memory search task. During test trials, the 16 younger and 16 older participants were shown probes and had to judge if the probes were part of the memory set or not.

Table 1

Summary of Studies on Cognitive Load

1st author, year	Independent Variable	Dependent Variable	Sample	Results	Effect Size
(11) Kahneman, 1966	*Cognitive Load: recall Digits (3 – 7), 4 HF nouns, transform 4 digits*	*Pupillary Diameter* during recall	5 female college students	Pupil diameter was highest for transform, then word, then digit task; memory span was highest for digits, next for words, and lowest for transformed digits	0.293
(10) Klinger, 2011, Exp. 2	*Digit Sequence Length and Modality; visual: 3 – 8 digits vs auditory: 6-8 digits*	*Pupillary Diameter* during digit retention interval	24 Stanford undergraduates with normal or corrected vision	Longer sequences associated with greater pupil dilation and poorer memory for both auditory and visual presentation modality	0.157
(9) Pajkossy, 2019, Exp. 1	*Size of Learning Set:2, 4, 8 word pairs*	*Pupillary Diameter* during recall, early pupil response	38 undergraduates	No significant difference in pupils between set sizes but significant difference in recall	0.020
(8) Pajkossy,	*Size of Learning*	*Pupillary Diameter*	38 undergraduates	Large set size associated	0.184

2019, Exp. 1	*Set:2, 4, 8 word pairs*	during recall, late pupil response		with largest pupil dilation and lowest recall	
(7) Piquado, 2014, Exp. 1	*Digit Sequence Length: 4, 6, 8 digits*	*Pupil Size* during retention interval	15 young and 15 older adults with normal or corrected vision	Larger sequence lengths associated with larger pupil sizes and poorer recall	0.624
(6) Piquado, 2014, Exp. 2	*Sentence Length: with or without word modifiers*	*Pupil Size* during retention interval	18 young adults with normal or corrected vision	Longer sentences were associated with larger pupil sizes and poorer recall	0.575
(5) Piquado, 2014, Exp. 2	*Sentence Length: with or without word modifiers*	*Pupil Size* during retention interval	18 older adults in good health	Longer sentences were associated with larger pupil sizes and poorer recall	0.687
(4) Piquado, 2014, Exp. 2	*Syntactic Complexity: subject-relative vs object-relative*	*Pupil Size* during retention interval	18 young adults with normal or corrected vision	Syntactic complexity was associated with larger pupils but no significant difference in recall accuracy	0.289
(3) Piquado,	*Syntactic Complexity:*	*Pupil Size* during	18 older adults in good health	No effect of syntactic	0.007

2014, Exp 2.	*subject-relative vs object-relative*	retention interval		complexity on pupils or recall accuracy	
(2) Van Gerven, 2004	*Sternberg Memory Load Task with 6 levels of memory load*	*Pupil Size* during search phase	16 young and 16 older adults with normal or corrected-to-normal vision	Reaction time to search memory and pupil size increased with memory load	0.165

Manipulations of Strength of Memory

Six studies were obtained that manipulated variables during encoding that affect the strength of the memory trace. The first study by Bradley and Lang (2015) used a within-subjects design with 65 participants and investigated the effect of the emotionality and repetitions of images presented during encoding on later recognition. Specifically, they showed participants neutral versus emotional (erotica and violence) images either once, repeated consecutively (massed), or repeated across the study (distributed). The next study by Kafkas and Montaldi (2015) manipulated the familiarity of word stimuli with a perceptual matching-to-sample task in two within-subjects experiments. The 44 participants in the first experiment had to provide a rating of familiarity, and the 34 participants in the second experiments had to answer "yes/no" if a stimulus was familiar. The third study by Naber et al. (2013) manipulated strength of memory trace by showing 16 participants novel versus familiar scenes; the experimenters used a mixed factorial design in which participants had to explicitly memorize the images for which subjective novelty and confidence ratings were later reported. The fourth study by Otero, Weekes, and Hutton (2011) reported three experiments, each with within-subjects designs, with 45, 34, and 37 participants, respectively. Otero and colleagues compared familiarity-based processes versus recollective-based processes using emotionally neutral words in experiment 1, depth of processing using acoustic stimuli presentation in experiment 2, and false versus veridical memories using new items semantically-related to old items at test in experiment 3. The fifth study conducted by Papesh, Goldinger, and Hout (2012) had 29 participants with manipulations of depth of processing using voice specificity in a within-subjects design. At test, a new voice or the same voice heard during encoding was heard, and participants made old/new judgments along with remember versus know judgments and confidence ratings. The sixth study was an unpublished thesis written by Taikh (2014) used between-subjects design manipulating depth of processing with 72 total participants. The participants studied randomly-assigned shallow, medium, or deep study lists and later made recognition judgments.

Table 2

Summary of Studies on Memory Strength

1st author, year	Independent Variable	Dependent Variable	Sample	Results	Effect Size
(17) Bradley, 2015	*Memory Strength: distributed vs single presentation of erotica*	*Pupillary Diameter* during recognition	65 University of Florida students	Distributed scenes elicited smaller pupils and faster recognition	0.186
(16) Bradley, 2015	*Memory Strength: distributed vs single presentation of erotica*	*Pupillary Diameter* during recognition	65 University of Florida students	Massed scenes did not enhance pupil diameter as much as new scenes; reaction times were faster compared to	0.116

				items seen once	
(15) Kafkas, 2015, Exp. 1	*Memory Strength: ratings of familiarity or novelty*	*Pupillary Reponses* during identification of old/new stimuli	44 native English speakers	Familiarity (old) ratings produced larger pupils than novel ratings	0.110
(14) Kafkas, 2015, Exp. 1	*Memory Strength: ratings of familiarity or novelty*	*Pupillary Reponses* during identification of old/new stimuli	44 native English speakers	Familiarity (old) ratings produced larger pupils than novel ratings	0.140
(13) Kafkas, 2015, Exp. 2	*Memory Strength: yes/no paradigm*	*Pupil Size* during identification of old/new stimuli	34 native English speakers	Pupils were larger for old targets compared to new	0.140
(12) Naber, 2013	*Familiarity of Target and Distractor Images: rated familiar vs rated novel*	*Dilation/Constriction* during image recognition	48 volunteers	Familiar scenes were associated with greater pupil dilation than unfamiliar scenes	0.321
(11) Naber, 2013	*Familiarity of Target Images: rated familiar vs. rated novel*	*Dilation/Constriction* during image recognition	48 volunteers	Pupil dilation was stronger for images judged as familiar compared to those judged as novel	0.059
(10) Otero, 2011, Exp. 1	*Familiarity of Neutral Words: remember vs.*	*Pupil Dilation* during word recognition	45 University of Sussex students	Pupil dilations were larger when correctly	0.065

	know judgments			recognizing old items	
(9) Otero, 2011, Exp. 2	*Depth of Processing: deep vs. shallow*	*Pupil Dilation* during word recognition	34 students	Pupil dilations and recognition were greater for deeply encoded items	0.184
(8) Otero, 2011, Exp. 3	*Item-Relatedness: target, critical distractor, noncritical distractor*	*Pupil Dilation* during word recognition	37 volunteers	Larger dilations for targets compared to critical distractors falsely recognized	0.248
(7) Otero, 2011, Exp. 3	*Item-Relatedness: target, critical distractor, noncritical distractor*	*Pupil Dilation* during word retrieval	37 volunteers	Greater dilation for critical distractors falsely recognized than to critical distractors correctly judged as new	0.081
(6) Papesh, 2012	*Voice Specificity: original, familiar, or new voice*	*Pupillary Diameter* during auditory test of old/new judgments	29 Arizona State University students	Peak diameters were larger during correct recognition	0.21
(5) Papesh, 2012	*Voice Specificity: original, familiar, or new voice*	*Pupillary Diameter* auditory test of old/new judgments	29 Arizona State University students	High confidence decisions were associated with larger	0.57

				pupils and greater accuracy	
(4) Papesh, 2012	*Voice Specificity: original, familiar, or new voice and nonwords vs. real words*	*Pupillary Diameter* auditory test of old/new judgments	29 Arizona State University students	Nonword presentation resulted in greater pupils; no influence of word type on recognition	0.48
(3) Papesh, 2012	*Voice specificity: Original, familiar, or new voice*	*Pupillary Diameter* during auditory old/new judgments	29 Arizona State University students	Pupils were larger and recognition more accurate when hearing the same voice during study and test	0.60
(2) Taikh, 2014	*Depth of Processing: deep vs. shallow*	*Pupillary Responses* During recognition	72 University of Calgary students	Deeper level of processing lead to larger pupil dilations and more accurate recognition than shallow level	0.12

Data Analysis

In essence, two meta-analyses were conducted, one for the influence of cognitive load and one for the influence of the strength of memory trace. For each independent study, including those with multiple experiments, F values and effect sizes (es) were obtained, either directly from the study or were calculated from statistics that were available in the studies. If F values were not directly reported, they were calculated using reported t values. Degrees of freedom (df1 and df2) were obtained from the studies. The effect sizes used are partial eta-squared; if partial eta-squared was not reported, it was calculated with the function F*df1/(F*df1+df2). The 95% lower and upper confidence intervals for the effect sizes were calculated, using a confidence interval calculator in which either the effect size or F-value and the degrees of freedom for each study were input. The weighting factor (w) was the sample size (n), so for purposes of consistency, n and w are synonymous but are presented as w. To obtain the weighted effect size, the effect size was multiplied by its respective w (w*es), then the sums of both w and w*es were obtained. The average weighted effect sizes for cognitive load and for the strength of memory were obtained by dividing the sum of w*es by the sum of w. The key for the cognitive load studies is in Table 1, and the key for the memory strength studies is in Table 2. Tables 3 and 4 provide the statistics for each study in the cognitive load and memory strength meta-analysis, respectively. The mean effect size is given in row 1 of these tables.

SECTION THREE: RESULTS

Cognitive Load Results

The sum of the weights and the sum of the weighted effect sizes were calculated ($\Sigma_w = 420.31$, $\Sigma_{w*es} = 100.33$) for the individual studies manipulating cognitive load. The weighted mean effect size was large ($\eta^2 = 0.2387$). The standard error of the effect size was calculated by taking the square root of one divided by w, (SEes = 0.048777), and confidence intervals were, 95% CI [0.1431, 0.3343]. A Z test revealed these scores to be 4.89 standard deviations above the population mean effect size of 0 ($z = 4.893$, $p < .01$, two-tailed). There is very little possibility of this value occurring due to chance. The forest plot with each individual effect size and the average effect size can be seen in Figure 1.

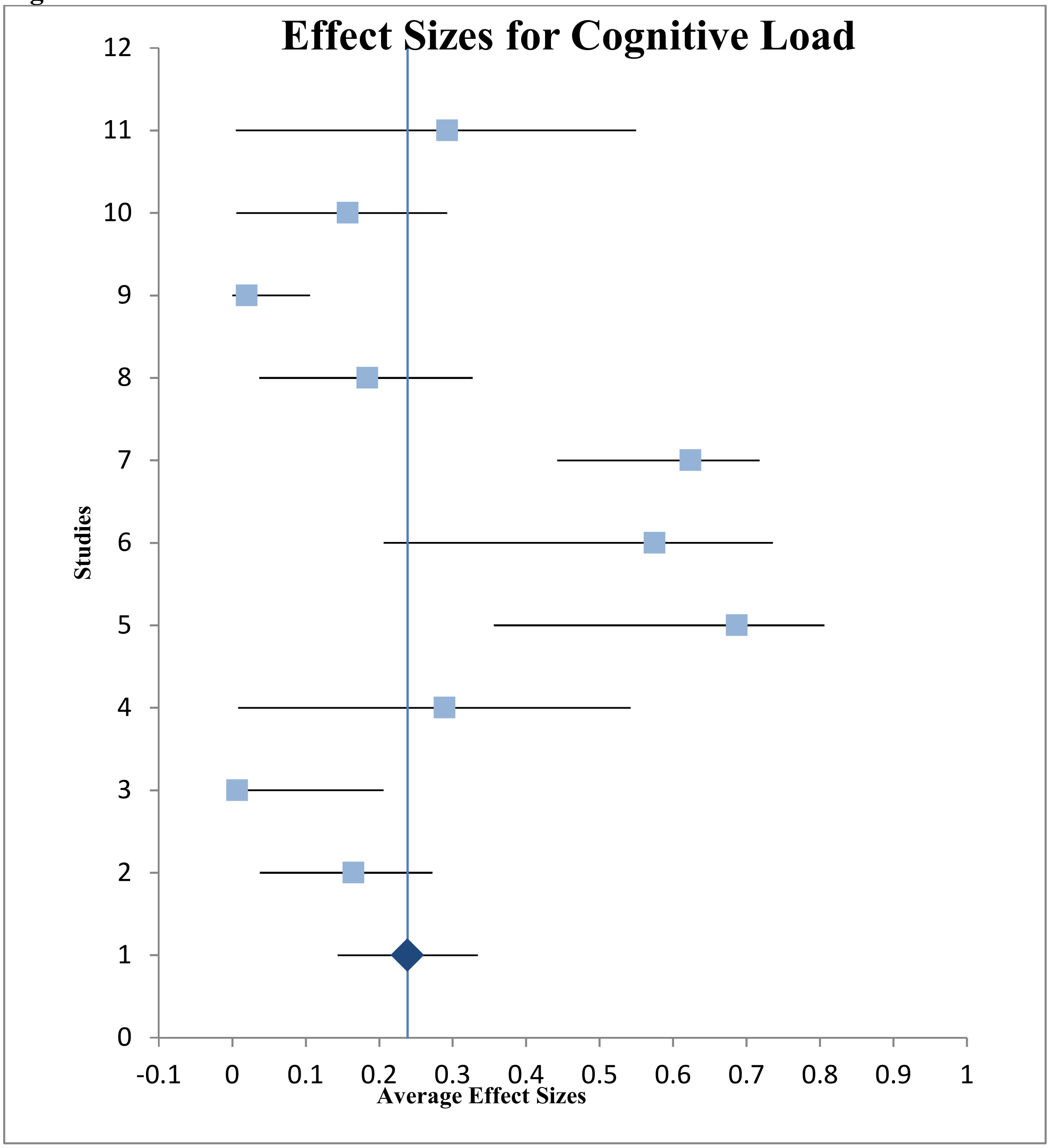
Table 3

Statistics for Studies Manipulating Cognitive Load

Key	**F**	**Df1**	**Df2**	**Partial η^2**	**95% Lower CI**	**95% Upper CI**	**w**	**w*es**
11.	6.62	1	16	0.293	0.005	0.550	16	4.682
10.	3.73	3	60	0.157	0.002	0.292	60	9.426
9.	0.73	2	68	0.020	0	0.106	68	1.360
8.	7.69	2	68	0.184	0.036	0.327	68	12.512
7.	46.56	1.93	53.91	0.624	0.442	0.718	53.91	33.640
6.	22.96	1	17	0.575	0.206	0.736	17	9.775
5.	37.23	1	17	0.687	0.356	0.806	17	11.679
4.	6.92	1	17	0.289	0.008	0.542	17	4.913
3.	0.120	1	17	0.007	0	0.206	17	0.119
2.	5.96	3.4	102.4	0.165	0.037	0.273	102.4	16.906
1.								0.239

Note: Row 1 reports the mean effect size, calculated by dividing the sum of column w*es by the sum of column w.

Figure 1.



Note: The key for the studies is located in Table 1.

Strength of Memory Results

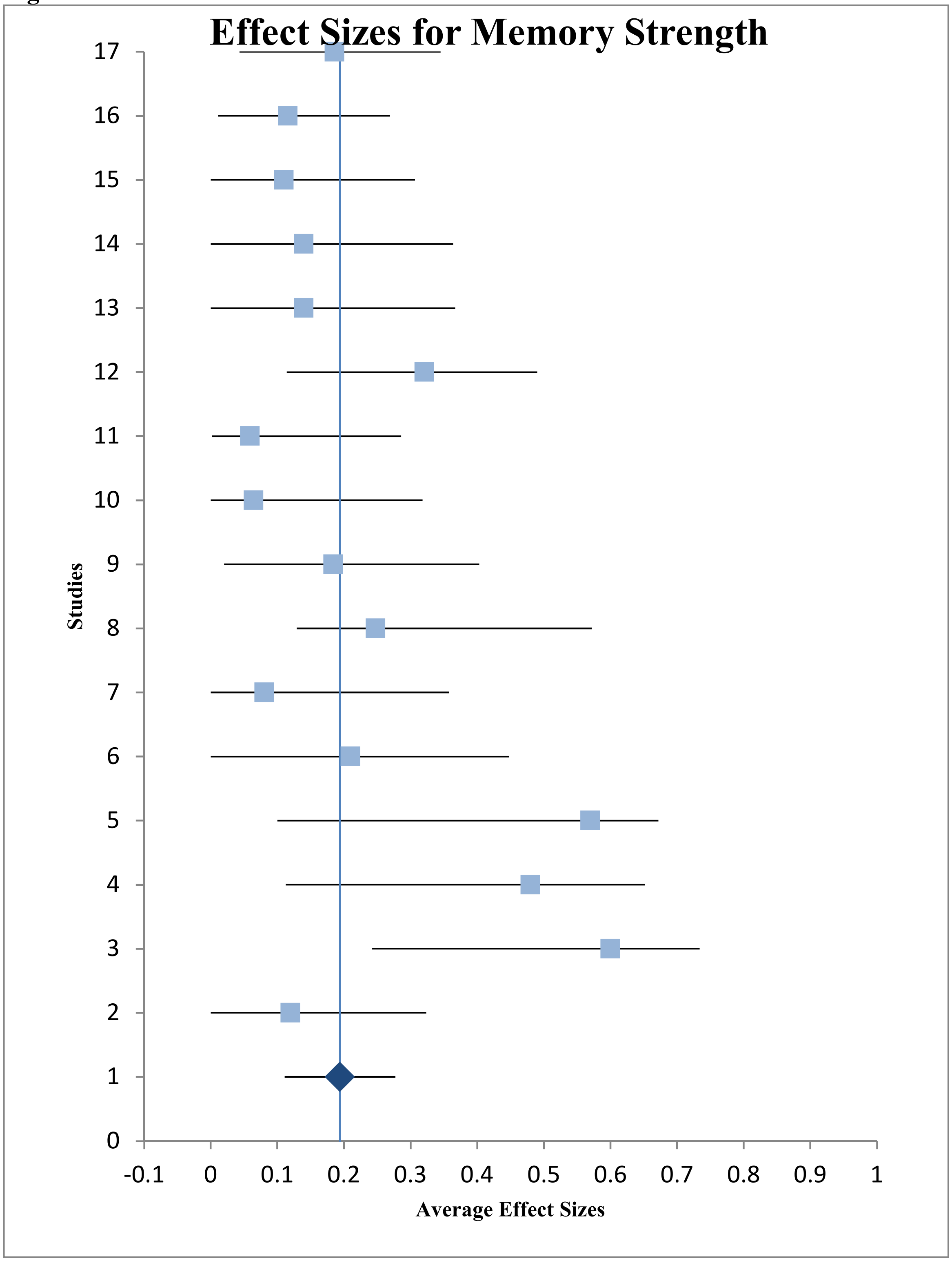
The sum of the weights and the sum of the weighted effect sizes were calculated (Σ_w = 558, Σ_{w*es} = 108.294) for the individual studies manipulating the strength of the memory trace. The weighted mean effect was large ($\eta^2 = 0.194$). The standard error of the effect size was calculated by taking the square root of one divided by w, (SEes = 0.042), and 95% confidence intervals were, 95% CI [0.111, 0.277]. A Z test revealed these scores to be 4.584 standard deviations above the population mean of 0 ($z = 4.584$, $p < .01$, two-tailed). There is very little possibility of these scores occurring due to chance. The forest plot with each individual effect size and the average effect size can be seen in Figure 2.

Table 4
Statistics for Studies Manipulating Memory Strength

Key	F	Df1	Df2	η_p^2	95% Lower CI	95% Upper CI	W	W*es
17.	14.4	1	63	0.186	0.043	0.345	63	11.718
16.	8.3	1	63	0.116	0.011	0.269	63	7.308
15.	4.39	1	36	0.11	2.63E-06	0.307	36	3.96
14.	4.51	1	28	0.14	3.33E-06	0.364	28	3.92
13.	4.62	1	28	0.14	3.33E-06	0.367	28	3.92
12.	22.18	1	47	0.321	1.14E-01	0.49	47	15.087
11.	5.856	1	47	0.059	2.0E-03	0.286	47	2.773
10.	4.84	1	36	0.065	2.63E-06	0.318	36	2.329
9.	6.76	1	30	0.184	2.0E-02	0.403	30	5.52
8.	20.43	1	32	0.248	0.129	0.572	32	7.93
7.	5.428	1	32	0.081	2.94E-06	0.358	32	2.579
6.	5.55	1	22	0.21	4.17E-06	0.448	22	4.62
5.	4.98	5	19	0.57	0.10	0.672	19	10.83
4.	9.33	2	20	0.48	0.110	0.652	20	9.6
3.	15.04	2	20	0.6	0.242	0.734	20	12
2.	4.81	1	35	0.12	2.7E-06	0.323	35	4.2
1.								0.194

Note: Row 1 reports the mean effect size, calculated by dividing the sum of the column w*es by the sum of the column w.

Figure 2.



Note: The key for these studies is located in Table 3 on page 16.

SECTION FOUR: DISCUSSION

The results indicate that both the amount of cognitive load during encoding and the strength of the memory trace have a significant influence on pupillary dilations and subsequent retrieval. As cognitive load and memory strength increase, pupil dilations also increase. Because the average weighted effect size of the influence of cognitive load is larger than that of memory strength, this suggests that the amount, complexity, and/or difficulty of information being encoded and the resources and effort available to maintain the information in one's working memory may have a negligibly larger effect on pupillary response during retrieval as compared to the strength of memory traces. Although there were more studies in the meta-analysis on the effect of memory strength, the evidence for a cognitive load effect was somewhat stronger.

During encoding, as the amount of information begins to exceed the amount of working memory resources, the pupils will continue to dilate until a limit is reached, after which the pupil diameters begin to decrease slightly (Zekveld & Kramer, 2014). Subsequently, recall is poorer as a result of increasing load due to the limited mental capacity to hold onto a large amount of information for retrieval (Paas & van Merriënboer, 2020). As supported by the large average effect size calculated, the impact of cognitive load on pupil size is quite important. The greater size of pupils during recall reflect the greater amount of cognitive load that results in poorer memory. The smallest effect calculated into the weighted effect size was from Piquado et al.'s (2010) experiment in which sentence syntactic complexity was manipulated. Although there was no significant effect of syntactic complexity on pupil size for older adults, pupils did dilate more during recall of the more complex, object-relative sentences compared to subject-relative sentences. The largest effect that was calculated into the average weighted effect size also came from Piquado and colleagues' study that replicated Kahnemann and Beatty's (1966) study manipulating digit list lengths. Not surprisingly, younger and older individuals' pupils dilated more during recall for longer digit sequences, but the longer sequences resulted in poorer retrieval. The poorer memory may reflect the limitations of working memory to maintain more than a few items at a time. Pajkossy and Racsmány's (2019) study shows similar effects in which increasing the set size of word-pairs resulted in larger late-pupil responses than did medium and small sizes and a decrease in accuracy of recall. The effect of set size did not have a significant influence on early-pupil responses. The authors suggest that larger late pupil responses could be due to higher processing load during recall, resulting in weaker memories.

The Van Gerven et al. (2004) study also resulted in a large average effect, showing again the inverse relationship between cognitive load and larger pupils and memory recall. As participants did the Sternberg memory task in which load and complexity increased, their pupil size increased, but reaction times and recall were poorer. In addition, the Klinger et al. (2011) study also produced a large average effect during which larger pupils were elicited during retrieval of larger sequences of digits. They also found that there is no significant difference in auditory or visual presentation in eliciting larger pupils, although auditory presentations have been seen to elicit slightly larger dilations. Overall, the greater amount, complexity, and difficulty of information held in working memory increases dilations but results in poorer recall.

The influence of strength of memory traces was also significant. The meta-analysis for this variable indicated that stronger memory traces were associated with larger pupil dilations and more successful recogntion. This reflects the relationship between the LC-NE system and the mental processes associated with manipulations of memory strength (Bergt et al., 2018). The different ways in which memory strength can be manipulated or measured, such as subjective confidence and levels of processing, have strong effects on pupil responses. The specific study that had the largest weight in influencing of memory strength was Naber et al. (2013) study of image recognition. Pupils were largest during retrieval for items previously seen that were successfully remembered compared to forgotten, a consistent pupil old/new pattern. In addition, deeper levels of encoding produced larger pupils and better recogntion compared to shallow levels of encoding across modalities, as demonstrated in both Otero et al.'s (2011) study and Taikh's (2014) study.

When comparing emotional old and new information, both pupil dilations and memory retrieval are greater for negative emotional stimuli, which is due to noradrenergic modulation in the locus coeruleus-noradrenaline system (Hämmerer et al., 2017). In this analysis, Bradley and Lang's (2015) study showed that repetition of emotional images has a powerful influence on recognition and pupil dilations, as the images of violence and erotica produced significantly large dilations compared to everyday images. More importantly, the effect of repetition had notable outcomes. Distributed and massed repetitions resulted in smaller pupil sizes during recognition but faster reaction times. The smaller pupils elicited by repetitons could be due to habituation of the repeated erotic images, and faster reaction times could be due to the strength of the memory trace from repeated presentation. This could be due to the the nature of the images producing cognitive arousal for faster recognition, but the potential effect of habituation in eliciting smaller pupil sizes needs further research.

Feelings of subjective confidence are also associated with larger pupil dilations. For example, of all of the data from Papesh et al.'s (2012) study, the largest average effect resulted from participants' ratings of high confidence in their answers as compared to the effects of correct versus incorrect recognition memory, word type, and voice congruency during study and test. In addition, as seen in Kafkas and Montaldi's (2015) study, larger pupil dilations were seen during recognition of old compared to new items. Also, feelings of both subjective and objective familiarity led to larger pupil dilations than feelings of novelty, but these did not produce quite as large effects as subjective confidence. The authors suggested that this pattern could be due to patterns in the brain in which distinct signals of familiary and novelty are incorporated to support retrieval of old information and encoding of new information, and pupil dilations are an output of the combined effort of encoding and retrieval. This is why pupils tend to smaller for stimuli better remembered during retrieval.

Greater cognitive load is associated with greater pupil dilation but poorer memory retrieval. Greater memory strength is also associated with greater pupil dilation but better memory retrieval. This difference could be due to the different types of memory and retrieval processes that occurred in each study and the brain areas in which these memory processes are occurring. For example, the studies manipulating cognitive load mainly looked at how short-term or working-memory was affected by differing amounts of load, such as by retaining lists of digits or complex sentences. The brain area associated with retaining information in working memory is the frontal lobe in response to frontal cortex activation that mediates working memory (Chai, Hamid, & Abdullah, 2018). Additionally, encoding sentences or digits visually or auditorally take different paths in brain to their respective cortical areas, resulting in different pathways for recall.

Further, the studies examining memory strength examined primarily episodic recognition memory and how subjective experiences impact retrieval. Episodic memories and emotionally-arousing memories are associated with stronger memories and greater pupil dilation. The brain areas associated with subjective feelings and emotions are subcortical areas, such as the limbic system and amygdala, that have unique projections to the hippocampus and can mediate noradrenergic activation (McGaugh, 2004). The neural processes associated with each of the studies vary due to the different studies from each and could result in the differences in pupil sizes and retrieval processes, some of which are conscious retrieval processes, such as retaining working memory, and some of which are unconscious, such as emotional arousal.

The are a few implications of this study. The influence of cognitive load on pupil dilations is evident, but its effect on neural processes for retrieval is more complex. As reflected by the studies, the neural processes associated with cognitive load may include separate pathways in the brain, and the brain may allocate different resources to different brain areas depending on the type of task, such as digit sequence recall maintained in the frontal lobes whereas associative learning is maintained by the hippocampus. Some limitations of this meta-analysis were the small number of studies collected due to the limited available resources in databases. Overall, the differences in the impact that cognitive load and memory strength have in successful memory may suggest differences in the neural pathways associated with each process. More research into the neurobiology is needed, perhaps with additional neurophysiological and neurocognitive measures, to determine what the differences may be. Future directions may focus exactly on these neural differences and ways to measure the amount of load and effort, as well the strength of one's memory. Additionally, future studies could examine Pajkossy and Racsmány's (2019) suggestion that under cognitive load, hippocampal projections create stronger memory traces to see if there are combined effects of cognitive load and strength of memory traces on pupil dilations and subsequent memory retrieval.

This meta-analysis examining how cognitive load and memory strength affect the size of the pupillary response during retrieval produced novel findings on the relationship between cognitive processes and physiological reactions that impact memory. Given the importance of successful memory for navigating daily life, this study helps bring to light the cognitive processes necessary for successful memory. Investigating differences reflected by pupillary responses that are due to different encoding processes and different amounts of attention and resources allocated during encoding can shed more light on techniques that scientists can use to track effort invested in the successful longer-term memory necessary for daily events and activities (Miller, Gross, & Unsworth, 2019). Pupillary responses during memory may also play an important role in clincal settings where cognitive processes have been affected, for instance, helping to understand changes in cases of individuals with amnesia (Laeng et al, 2007).

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