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PUPILLOMETRY REVEALS INSIGHT INTO METACOGNITIVE PROCESSES DURING ENCODING

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by

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ABSTRACT

PUPILLOMETRY REVEALS INSIGHT INTO METACOGNITIVE PROCESSES DURING ENCODING

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Metacognitions are the processes associated with how well we learn and monitor our study behavior. This can be assessed with judgments of learning (JOLs) during encoding of cue-target word pairs (e.g., dog – bowl), which are predictions on how confident we are that we will remember the target (e.g., bowl) when later presented with the cue (e.g., dog) at retrieval. The easily learned easily remembered (ELER) heuristic states that the easier it is to learn something, the easier it is to be remembered later. However, recent studies using eye tracking show that more effortful encoding, as indexed by larger pupil sizes, is associated with better memory. To arbitrate between these two alternatives, participants studied four separate randomized lists of 24 words consisting of 12 related (e.g., dog – bowl) and 12 unrelated (e.g., table – shoe) cue-target pairs. Pupil size was measured during the 5-second encoding period and JOLs were taken after learning each word pair. Following study of each list, participants were given a 1-minute distractor task followed by a cued recall task in which participants tried to recall each target when presented with the cue. It was found that JOLs, recall accuracy, and task-evoked pupillary response (TEPR) were all greater with the related word pairs compared to the unrelated word pairs, arguing against the ELER heuristic. These results have important implications for education, especially for increasing long-term memory.

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CHAPTER 1

INTRODUCTION

Metamemory refers to the processes associated with assessing how well information has been learned (monitoring) and appropriately allocating resources to studying (Serra & Metcalfe, 2009). Metamemory has important implications for student learning outcomes, as ineffective monitoring may lead to suboptimal study habits for students. Behavioral research shows that items that are more easily learned (as measured through higher judgements of learning (JOLs) or shorter study durations at encoding) are often better remembered (Koriat, 2008). However, recent studies using eye tracking show that more effortful encoding, as indexed by larger pupil sizes, is associated with better memory (Unsworth & Miller, 2021). The purpose of the current study is to resolve these discrepancies by examining the relation between JOLs, pupil size, and subsequent memory.

1.1 Metacognition

Metamemory is the information that a person consults when they are thinking about memory. This includes knowledge about the task (metacognitive knowledge), one's perceived ability to perform that task (monitoring), and any strategies to use to perform the task (control). Metacognitive monitoring is often assessed via JOLs, which are the evaluation of one's memory and how well they will remember the learned material on a scale from 0-100%. The relation between JOLs and subsequent memory is typically assessed via calibration and/or resolution. Calibration is the difference in score between the mean of one's JOLs and their actual memory performance on the task, while resolution is the measure of how well one's judgments predict memory performance on an item-by-item basis. Research suggests that although participants may be over- or under-confident in their memory ability (calibration), they are often relatively accurate in the predictions (resolution). Previous studies have found that factors such as relatedness of material are studied for less time but have higher JOLs and increased accuracy of retrieval (Serra and Metcalfe, 2009).

1.2 Easily Learned Easily Remembered (ELER) Theory

Research suggests that participants can make use of a variety of cues, including intrinsic, extrinsic, and mnemonic. Intrinsic cues include characteristics of the study items that can disclose and be perceived of their ease or difficulty (e.g., word relatedness). On the other hand, extrinsic cues are factors that are related to the learning process and encoding effort by the learner (e.g., encoding operations). Mnemonic cues are used based on their experience on performing the task (e.g., easily learned easily remembered) (Koriat, 1997). Research has shown that intrinsic (relatedness) / mnemonic cues (study duration) can be a strong predictor of performance. For example, the easy learned easily remembered (ELER) heuristic states that the easier it is to learn something, the easier it is to be remembered later. For example, simplicity, familiarity, and predictability of the learned material cause the study duration to be shorter compared to more effortful learning material, and these more are associated with higher JOLs during learning and better memory at retrieval. This is due to the judgment that with easier items, there tends to be a stronger feeling of confidence and proficiency in the learned material, due to cue utilization and the short learning time of the material (Koriat, 2008).

1.3 Pupil Size and Pupillometry

Recent evidence suggests that pupil size can be a reliable indicator of encoding effort (Unsworth & Miller, 2021). Pupillometry is the study of continuous change in pupil size in response to different stimuli. Pupil constriction and dilation are known to be affected in response to different visual stimuli, such as the brightness of light and focusing on the near fixation of an object but can also reflect distinct cognitive operations occurring in response to the stimuli. For example, pupillary measures can reliably index the amount of attentional effort devoted to the task (i.e., intensity) and how efficiently attention acts (i.e., speed).

Pupil dilation is controlled by the iris dilator muscle, and it is affected by the hypothalamus and the locus coeruleus (LC). Both the LC and hypothalamus become active once the brain is in an aroused state and follows the neural pathway to the intermedia-lateral column (IML) of the spinal cord, then to the superior cervical ganglion (SCG), and finally to the iris dilator muscle (Mathot, 2018).

The brain can become aroused by norepinephrine (NE), a transmitter that affects the body into an alert and wakened state. The release of NE from the post synapse stimulates both the $\alpha 1$- and β-receptors within the LC to give a synergetic effect of brain arousal (Berridge, 2007). Norepinephrine is a product that originates from dopamine, a neurotransmitter associated with pleasure and satisfaction, through the incorporation of a hydroxyl group. Both dopamine and NE are products from the hydroxylation and decarboxylation of L-tyrosine, an aromatic amino acid (Wassal et al., 2009).

Pupil size is an indirect index of the functioning of the locus coeruleus-norepinephrine system, which is integral for regulating attention and arousal. Whenever the pupil is dilated, more light is allowed into the eye. This allows for more information to be received to the brain and is often correlated with higher encoding effort. Phasic activation of the LC that increases pupil size is driven by the outcome of task-related decision processes to increase gains from the task (Mathot, 2018).

Human behavior is based on two bases: exploitation and exploration. Exploitation is engaging in a single task, while exploration is being easily distracted from the original task and switching to another task. The adaptive gain theory of behavior states that we alternate from exploitation and exploration to optimize our reward. During exploitation, the LC becomes phasic and causes the pupil to be an intermediate size, while during exploration, the LC becomes tonic and causes the pupil to dilate to a larger size (Aston-Jones & Cohen, 2005).

Based on pupil physiology, this allows researchers to monitor attention regulation through pupillometry by focusing on the mean amplitude of pupil size following stimulus onset. This is referred to as a task-evoked pupillary response (TEPR). Other measures of pupil size include variability of mean amplitude and peak latency onset (i.e., the amount of time it takes to reach max amplitude). Central to the current study, it is found that TEPRs may index the amount of cognitive effort during encoding

1.4 Pupillometry and Memory

Evidence suggests that encoding effort can reliably be indexed by mean pupil size (Kahneman & Beatty, 1966; Unsworth & Robison, 2018). Research shows that pupil size scales with attentional load (Robison et al., 2018), memory load, and value (Ariel & Castel, 2014). Critically, the larger the pupil size during encoding, the higher the accuracy of recalling the information (Papesh et al., 2012). Further studies have also shown that the greater the cognitive effort during encoding, the larger the pupil size and the higher the accuracy rate of retrieval. Specifically, the highest peak diameters were associated with strong memory strength during encoding and retrieval. In general, studies in pupil size revealed the differences in the amount of cognitive effort given for high frequency and low frequency word pairs. The subsequent memory paradigm is used to identify brain activity elicited during episodic encoding with successful subsequent retrieval. Using this, we can compare neurophysiological measures and tests to differentiate the neural activity associated with subsequently remembered versus forgotten information (Kamp et al., 2017).

1.5 Pupillometry and Metacognition

While there are multiple studies that focus on the relationship between pupil size and memory, there are few studies that focus on the relationship between pupil size and metacognitive confidence at encoding (e.g., JOLs). As described previously, Papesh et al. (2012) examined confidence only at retrieval, showing that higher pupil size was correlated to higher retrieval scores. On the other hand, Kelly (2021) examined JOLs at encoding while tracking pupil size but focused specifically on biofeedback. Kelly showed that participants strongly utilized their pupil cues and pupil size information to inform their JOLs. Thus, it remains unclear whether pupil size is associated with confidence at encoding. Moreover, there are competing predictions based on current theoretical accounts and existing data.

The *ELER heuristic* predicts that pupil size should be smaller and JOLs should be higher for items that are easier to learn (e.g., high cue-target associations) compared to items that are more difficult to learn (e.g., low cue-target association). In support of this idea, Kafkas & Montaldi (2011) had participants incidentally encode pictures and stimuli were rated by retrieval rates during the retrieval period. It was found that pupil response and fixation patterns at encoding predicted later recognition memory strength. However, as reviewed previously, many of the pupillometry studies contradict this hypothesis and instead suggest that higher pupil size should predict high JOLs and better memory (Papesh et al., 2012), which we will refer to as the *encoding effort hypothesis*.

1.6 Current Study

To arbitrate between predictions from the ELER heuristic or the encoding effort hypothesis, the current study had participants study four blocks of 24 words, each containing 12 related word pairs and 12 unrelated word pairs. We measured each participant's pupil size and JOLs during encoding, along with their accuracy during retrieval. This was done to test the idea that pupil size should be smaller with items requiring lower encoding effort and therefore should have higher JOLs. We also expected to see lower brain arousal and awareness with lower encoding effort.

CHAPTER 2

METHODOLOGY

2.1 Design and Participants

A 2-level word relatedness test (related vs. unrelated) within-subjects design was employed. A total of 51 undergraduates from the University of Texas at Arlington enrolled in the study to receive participation credit towards course requirements. The task was completed online using E'Prime Go and took approximately 35 minutes to complete.

2.2 Materials

The stimuli included 96-word triplets that were referenced from the Florida Association Norms, with two counterbalanced word lists being created. For example, for the word triplet dog-bowl-table, the two counterbalanced lists either had high relatedness (dog-bowl) or low relatedness (dog-table). The relatedness/unrelatedness from the word triplets were randomized between the two lists. In total, there were 24-word pairs per learning block, with 12 related word pairs and 12 unrelated word pairs.

In terms of measuring pupil size, an eye tracking software called gaze point was used when the participant is learning the word pair at a 150Hz sample rate. The eye-trackers use infrared cameras built into the frame, are mounted directly to the computer, and are synchronized precisely with the stimulus-delivery software to allow millisecond-level temporal precision and micrometer visual angle precision in pupil diameter and gaze changes. Participants were tested individually in a dimly lit room with no windows so we could eliminate the natural effects of light intensity on pupil size.

2.3 Procedure

2.3.1 Procedural Details

There were four learning blocks of 24-word pairs, which consists of a study period, distraction test, and recall task. During the study period, the participants first maintained fixation at center of screen, and when presented with the word pair, they studied the word pair for five seconds. After learning each word pair, participants were asked to make their JOL on a scale from 0-100, then pressed enter to learn another word pair. For the distractor test, participants solved multiplication problems for one minute and must maintain 50% accuracy. While there is no programming to make sure participants maintained 50% accuracy, telling the participants this information allows them to put in full cognitive effort that is purposeful of the distractor task. After the distractor test, participants entered the recall period, where they were presented with the first word of the word pair that they have previously learned and were asked to type in the second word. If the participants did not remember the second word, they were free to guess the second word. Once the learning block is completed, they were presented with a new word list to learn and continued the tasks until they have completed four learning blocks.

As a reminder before starting the task, participants were given the following instructions:

> "For this experiment you will learn words, make confidence judgments about how likely you will remember the words, then your memory for those words will be tested. Specifically, you will learn two words, such as table and pencil. During the test, you will be prompted with the first word (table), and you will type in the second word (pencil). After each pair you

study, you will type in a number between 0-100. That number is the likelihood you think you will remember the word pair. For example, you will type in 80 if you are 80% sure you will remember the pair. Please use the whole range of numbers depending on your confidence. You will complete four learning and test blocks."

2.3.2 Post-Experimental Questionnaire

At the end of the experiment, the participants were given the following questionnaire about the task. This included asking how motivated they were, how interested they were in the task, how easy/difficult the task was, how unpleasant the task was, and how to best describe their performance. These were rated on a scale of 1-5 (e.g., 1 completely unmotivated, 5 completely motivated). They were also asked what strategy they predominantly used throughout the task to remember the pairs. After completing the questionnaire, the participants were debriefed about the experiment and granted course credit.

2.4 Data Analysis

The pupil diameter for all experiments is continuously recorded binocularly at 60 Hz using a GazePoint eye, resulting in 300 observations across the 5 second trial. Any measurements outside a reasonable range (< 2mm or > 8mm) were filtered and any participant missing more than 40% of their data is excluded from analyses. Task-evoked pupillary responses were corrected by using the 1000ms bin as a baseline to standardize within an individual (Robison et al., 2022). This was done because there was a strong pupillary light reflex until around 800ms corresponding to the change in luminance between the pretrial fixation and stimulus onset.

To explore effects of interest, performance measures (JOLs, TEPR, accuracy) were analyzed with within-subject ANOVA comparing related and unrelated words. Follow-up analyses for JOLs and TEPRs were conditionalized on whether they subsequently remembered (acc = 1) or forgot (acc = 0) that item. To do this, we ran an ANOVA that included relatedness (related vs. unrelated) and accuracy (accurate vs. inaccurate) for both JOLs and TEPRs.

CHAPTER 3

RESULTS

3.1 JOLs (Encoding)

The analysis of JOLs revealed that participants were more confident for the related word pairs (*M* = .68, *SE* = .03) than with the unrelated word pairs (*M* = .36, *SE* = .02), $F(1,50) = 241.76$, $p < .001$, $\eta_p^2 = .83$ (Figure 3.1).

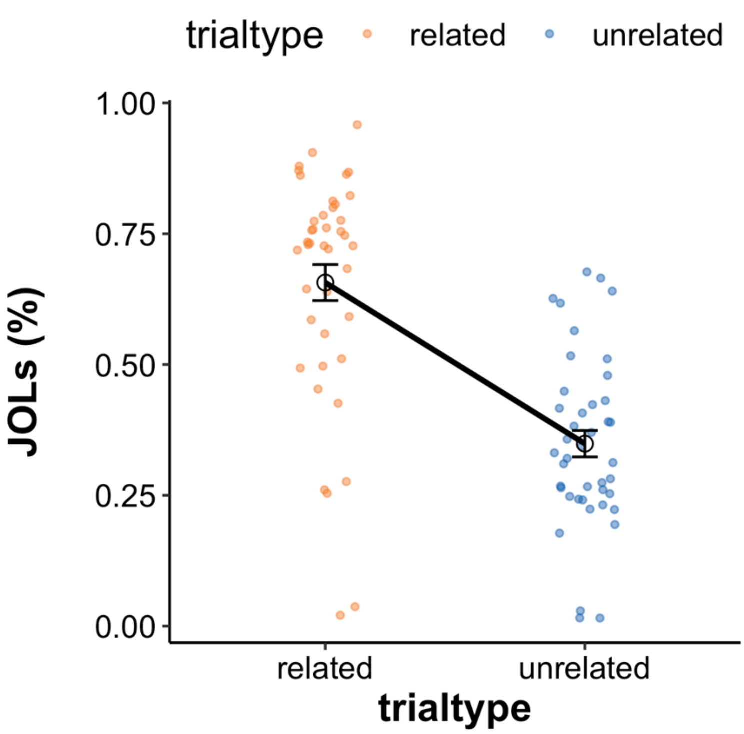

Figure 3.1: JOLs between related and unrelated word pairs

3.2 Accuracy (Retrieval)

The analysis of accuracy revealed that participants were more accurate for the related word pairs (M = .76, SE = 0.02) than with the unrelated word pairs (M = .26, SE = .03), $F(1,50) = 649.64$, $p < .001$, $\eta_p^2 = .93$ (Figure 3.2).

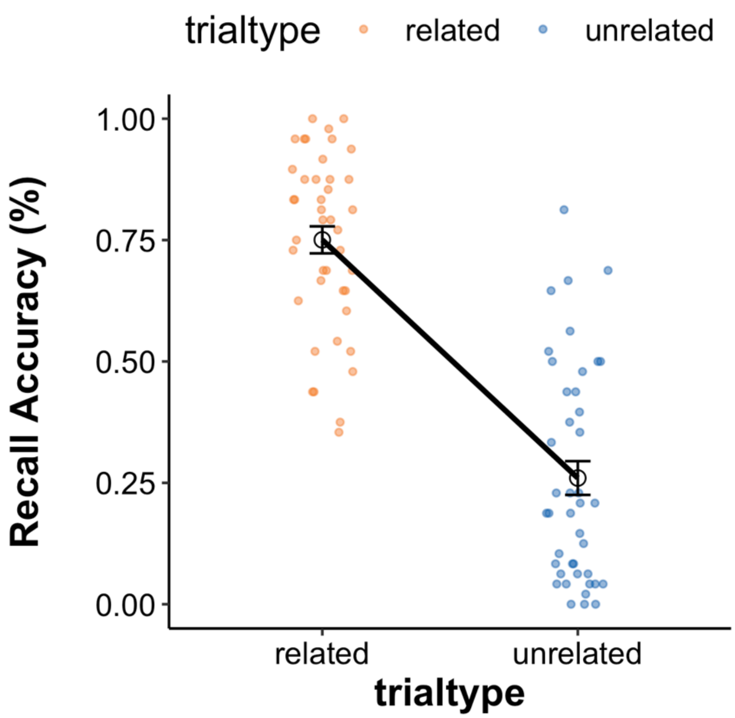

Figure 3.2: Recall accuracy between related and unrelated word pairs

3.3 Task Evoked Pupillary Response (TEPR) (Encoding)

The TEPR mean for the related word pairs was significantly higher than the TEPR mean for the unrelated word pairs (Figure 3.3).

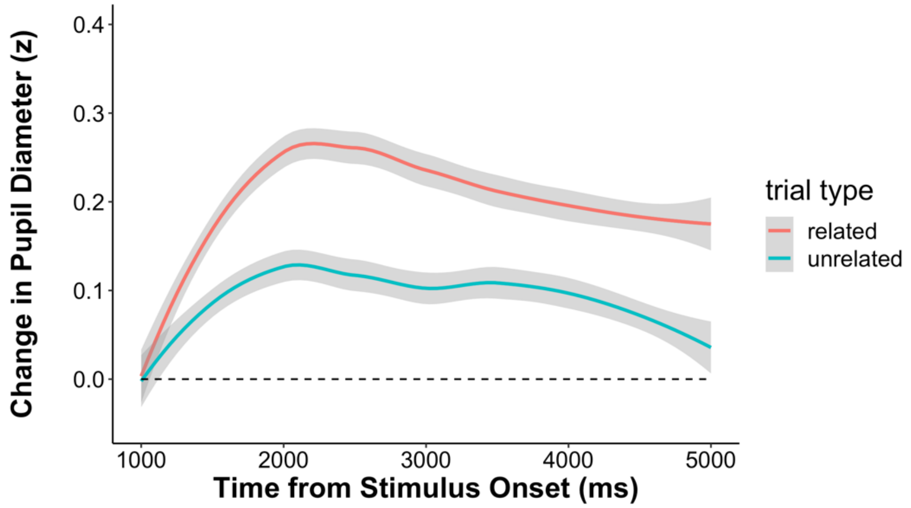

Figure 3.3: Mean TEPR between related and unrelated word pairs

3.4 Conditionalized Performance

3.4.1 JOLs (Encoding)

The analysis of JOLs revealed a main effect of relatedness, such that participants were more confident for the related word pairs (M = .66, SE = .21) than with the unrelated word pairs (M = .39, SE = .19), $F(1,45) = 181.64$, $p < .001$, $\eta p2 = .80$. There was also a main effect of accuracy, such that participants were more confident for the accurate pairs (M = .58, SE = .41) than with the inaccurate pairs (M = .48, SE = .19), $F(1,45) = 30.80$, $p < .001$, $\eta p2 = .41$. There was no interaction between the two, $F(1,45) = 3.30$, $p < .076$, $\eta p2 = .07$.

3.4.2 TEPR (Encoding)

The analysis of TEPRs revealed a main effect of relatedness, such that participants had a larger pupil size for the related word pairs (M = .24, SE = .38) than with the unrelated word pairs (M = .11, SE = .35), $F(1,43) = 11.26$, $p < .002$, $\eta p2 = .21$. There was also a main effect of accuracy, such that participants had a larger pupil size for the accurate pairs (M =

.18, *SE* = .35) than with the inaccurate pairs (*M* = .18, *SE* = .38), $F(1,41) = .01$, $p < .93$, $\eta p2 = .000$. There was no interaction between the two, $F(1,43) = 3.15$, $p < .08$, $\eta p2 = .07$.

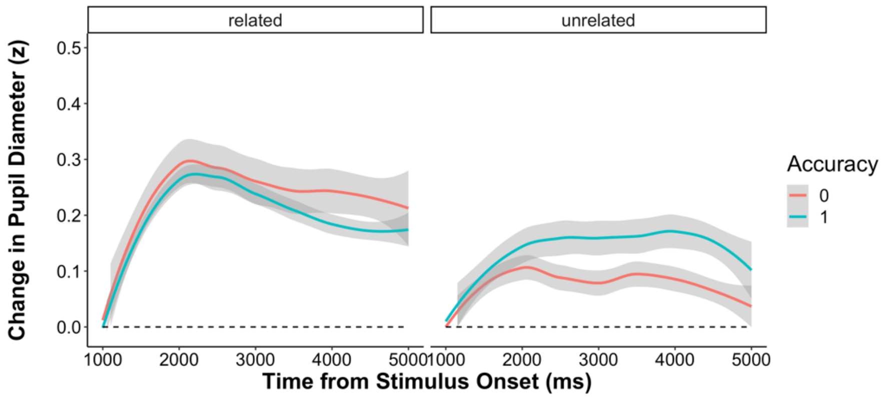

Figure 3.4: Mean TEPR between word relatedness and recall accuracy

CHAPTER 4

DISCUSSION

The purpose of the current study was to test the ELER heuristic in relation to JOLs, pupil size, and subsequent memory. Contrary to predictions from the ELER theory, we found that related items resulted in larger pupil size, higher JOLs, and better recall accuracy than unrelated items. These findings suggest that the encoding effort hypothesis may better account for the findings, with related items receiving more effortful encoding, which increased confidence and subsequent recall.

There are two types of self-regulated learning, depending on the environmental circumstances. With the regional of proximal learning, we tend to study items that are within our grasp when given limited study time, so easier items tend to be studied the most. However, with unlimited study time, we tend to utilize discrepancy reduction and study the more difficult items to achieve a desired level of mastery (Son & Metcalfe, 2000). For example, Son and Metcalfe gave participants two types of essays to read: one “easy” essay and one “hard” essay. There were two experimental groups, with one group given a limited amount of time to study and the other given no study time constraint. The results showed that participants were adaptive in their study habits depending on their condition. When time was limited, participants focused on the easier items, and when time was unlimited, participants focused on the harder items. In the current study, participants were given limited study time; further extension of this research can include allowing participants unlimited study time and seeing how our results compare across groups.

During encoding, there is a limited number of mental resources available to learn the material. Instead, we tend to allocate these resources to maximize the yield of beneficial outcomes for ourselves. In terms of our experiment, it is easier to utilize strategies to learn the related word pairs (e.g., form mental images) compared to the unrelated word pairs. Since the unrelated word pairs were more difficult to encode and recall, the participants may have given up on learning these types of word pairs later in the trials. Pupil size could reflect not necessarily the effort but the ability to engage in elaborative encoding strategies or overall interests in the task.

Another limited resource that we have is our NE levels. Our bodies can catabolize only so much NE based on our reaction time and starting levels of dopamine, so these resources must be allocated sparingly. In the case of limited study time, focusing on the easier items allows for more efficient use of NE, especially since less effortful strategies are needed to learn the material. By allowing for more use of NE and allowing for pupil size to dilate, we can maximize the study effort and allow it to be even easier to study the related materials. This option allows for more light and information to be received into the brain. Going back on the theory of adaptive gain, we alternate from exploitation and exploration to optimize our reward. With limited NE levels, it is better to exploit what we have and focus on one item than be wasteful and try to shift difficulties. In general, higher arousal within the brain with easier study materials maximizes our beneficial yield in the end.

As explained before, the ELER states that with easier study material, the less encoding effort is needed and therefore the smaller the pupil size becomes. The results of the current study clearly suggest that this isn't the case. The current theory can be updated based on the findings of this experiment with extrinsic cues on interest about the task at hand and response time per given material (mnemonic cues).

4.1 Limitations

Within our study, there is the limitation of computer errors that could have interfered with the participant's ability to complete the task. These errors occurred randomly and are completely out of our control but did influence how smoothly the participant's trials could have gone. We also found that throughout our data, there were some data points that were spread throughout our usual data range, creating a lot of "noise" within our analysis. This can be due to the small trial count throughout our experiment due to a time constraint. Having more trials not only could fix our data set but can also test the theory of under confidence with practice.

CHAPTER 5

CONCLUSION

From our research study, we found that pupil size was larger for related items compared to unrelated items, as well as higher JOLs and recall accuracy for these items. Following the basis of this experiment, we can assess encoding effort and recall accuracy based on pupil size. This can be applied to educational purposes by tracking students' encoding effort during learning and can be a predictor of recall accuracy. It can also be an indicator of the difficulty of the material given and how well students are learning it. In general, long-term memory can be improved as indicated by the strategies and findings of this experiment.

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BIOGRAPHICAL INFORMATION

Britney Le was born in San Jose, California, but later moved to Mansfield, Texas, and has lived there ever since. She is the oldest daughter of Becky Tran and Brandon Le and has two younger siblings, Brianna Le, and Brayden Le. She also lives with her grandmother Van Tran and is a proud pet owner of a miniature Australian Shepherd, Chewie. She graduated from Lake Ridge High School in 2019 with a 4.0 GPA and has also obtained her Pharmacy Technician Certification during her senior year. Because of her certification, she has been working as a certified pharmacy technician for three years and currently works for Kroger Pharmacy. Others see her as a healthcare hero for providing COVID-related services, such as testing and vaccinations, to the public throughout the pandemic.

Britney is currently a fourth-year student at the University of Texas at Arlington (UTA), majoring in both biology and interdisciplinary studies (biochemistry, psychology, and medical humanities). She is very active in many extracurriculars offered at UTA, such as Global Medical Training, Minority Association of Pre-medical Students, the Leadership Honors Program, and the Honors College. One of her favorite parts of attending UTA is the opportunities to travel and serve in medical mission trips to Central America, where she has worked with other students to provide free medical and dental services to areas deprived of healthcare access. After completing her bachelor’s degree, her main goal is to attend medical school and practice pediatric medicine.