Accessing Long-Term Memory – What Pupil Dilation Can Tell Us About Search Processes: An Exploratory Study

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Memory research has been conducted for more than a century and has led to a general understanding of how memory functions. In 1890, James suggested a two-component memory system consisting of primary (PM) and secondary memory (SM) systems. He theorized that PM holds all the items of which we are consciously aware, while SM holds all remaining memories. Baddeley and Hitch (1974) expanded James's idea by proposing a multi-component working memory system that regulates the various memory storage systems. Cowan's focused attention model (1995) then suggested that all information is stored in just one multi-dimensional memory system, and that the key issue is whether certain memories are currently activated (as cited in Unsworth & Engle, 2007). He suggested that our awareness of memories simply relies on focused activation of a particular memory, often referred to as working memory capacity (WMC). Much research has investigated how pupil size correlates with WMC and mental effort during both simple problem-solving as well as complex tasks. In most of these studies, researchers reported mean differences in pupil size. Although this is a necessary start, it does not allow for detailed understanding of how search processes work. Our research is interested in providing more detailed insight into the levels of activation in relation to pupil behavior by investigating pupil dilation during the learning and later retrieval processes. This will be the first study to investigate step-by-step pupil dilation during the recall process.

A large body of evidence has shown that pupil size is a reliable indicator of arousal state, overall attention levels, and mental effort. (For a comprehensive review of the pupillary system, see Beatty & Lucero-Wagoner, 2000.) In 1964, Hess and Polt showed that pupil size is strongly related to task difficulty. Their research focused on asking participants to solve mathematical problems. The researchers measured pupil size before trials (baseline) and during recall to determine the mean difference between both phases. Hess and Polt found that during each trial, pupil size gradually increased while participants tried to solve each problem reaching maximum dilation just before giving an answer, a clear indicator of mental effort. They also reported an almost perfect correlation between pupil size and task difficulty; the more difficult a math problem was, the more participants' pupils dilated.

Kahneman and Beatty (1966) further explored Hess and Polt's findings by presenting evidence for the impact of memory load on pupil size. Participants showed significantly higher pupil dilation for 7-word memory trials than for 4-word trials. Participants also reported intensive rehearsal during the 2-second pause between the presentation of the last word and the initiation of the recall phase. This rehearsal was evident in maximum pupil dilation. During the presentation of to-be-learned words, pupil size gradually increased and reached maximum dilation during the short pause before recall. The pupil then gradually decreased with each reported word to slightly lower than baseline levels before eventually returning to baseline condition in time for the next trial. It therefore appears that pupil dilation is a direct measure of cognitive load and quite possibly shows the amplitude of cognitive processes during both encoding and retrieval mechanisms.

More recent studies have suggested possible control over how much effort can be exerted during a task (Heitz, Schrock, Paye, & Engle, 2008; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010). More specifically, Heitz et al. (2008) showed that individuals could be enticed to put forth more effort and work harder at a task when given feedback and a monetary incentive. They reported a higher performance in the feedback and reward condition than in the control condition. The researchers showed that in the control group, high-functioning WMC individuals have more control over their attention levels and thus outperform low-functioning WMCs. More importantly though, their results revealed that both high- and low-functioning WMC individuals could be enticed to put forth more effort and that both had the ability to control their attention.

As Gilzenrat et al. (2010) suggested, an individual's control over attention is important in increasing our understanding of reduced attention functioning in individuals suffering from attention deficit disorder. The researchers reiterated the findings of Heitz et al. and suggested that individuals might have more control over their attentive states than was previously assumed. In their experiment, Gilzenrat et al. gave participants an escape option: Individuals had the choice to reset task difficulty once the trials became too hard for them to solve. As with other studies, pupil diameter gradually increased with task difficulty and, interestingly, reached maximum dilation right before the participant chose the escape option. More importantly, trials immediately following the escape showed a closer-to-baseline pupil size that first increased with performance only to decrease again with an increased task difficulty. Gilzenrat et al. clearly showed how participants could willfully reset their attention level by starting fresh with a lower difficulty trial. During their experiment, participants repeated this pattern continuously. With increased numbers of trials, participants also chose to escape more often and earlier, a sign of overall decreases in attention and task interest levels.

To our knowledge, Engle (1975) was the first to highlight this phenomenon in detail. In his experiment, Engle gave participants lists of words to remember for later recall. During the trial, the pupil size of the participants rapidly increased with the first few words and then became relatively stable. After participants received a cue to initiate recall, their pupil diameters increased again, a possible sign of intense search effort. During recall, pupil size decreased with each item recalled. This pattern was repeated in all trials but with decreasing amplitude. It appears that over time, overall attention levels decrease and never quite reach the intensity of the first trial. This might be a sign of lack of novelty as well as participants' decreased interest in the task at hand.

The phenomenon of decreasing attention levels within trials deserves more study. Many studies have demonstrated primacy and serial position effects (Rundus & Atkinson, 1970; Murdock, 1962; Deese & Kaufman, 1957), but none have done so using pupil dilation as a proxy for attention. The power of primacy effects is largely attributed to the number of rehearsals each list item receives (Rundus, 1971). Thus, early list items and especially the first item benefit greatly as participants have more time to rehearse these earlier items. Given that participants' attention levels decrease over the course of a trial (Murphy, Robertson, Balsters, & O'Connell, 2011), the probability of recall is not only a function of serial position (Murdock, 1962) but also of attention. Although the list position of an item is strongly associated with successful recall as first and last items are more likely than middle items to be recalled (Deese & Kaufman, 1957), it is worth investigating what role attention plays in this context. Because of possible fatigue or lack of interest within a trial, participants put forth less effort and attention as the trial continues. Theoretically then, later items receive less attention than earlier items and cannot be recalled as effectively in a delayed free recall task.

Previous research has shied away from a detailed analysis of pupil size during the recall period, something that this exploratory study aims to provide. It is possible that said fluctuations were harder to detect with technology available during earlier experiments, such as Engle's (1975). With modern advances in pupillometric technology, we can measure pupillary changes with much better precision, resolution, and timeliness. If we can compare attention as reflected in pupil size fluctuations during the encoding process and the attentive states during the retrieval process, we will likely detect links not only between these two processes but also learn more about how exactly the retrieval mechanisms work. In the present study, we expect to reveal distinct pupil dilation patterns during both the learning and recall phase. Specifically, we expect the pupil to increase during the learning phase, increase before the onset of recall, and then decrease during retrieval. Furthermore, this exploratory study investigates known primacy effects. Could the likelihood of accurate recall of the first word be associated with pupil size, and with that, attention levels?

Method

Participants

For this exploratory study, we recruited 22 participants from the Human Subjects Pool and the research cohort at the University of Oregon. One participant had to be excluded because of an inability to maintain eyes on screen during the recall (typing) phase, thereby invalidating the pupil data for that session. A second participant was excluded because of a hardware failure shortly after the start of the experiment. Both of the excluded participants received class credit. The remaining sample consisted of 20 participants (M_{Age} = 22.05, SD = 4.15). Of the participants, 15 were undergraduate students who received class credit for their participation.

The remaining 5 participants were drawn from the researcher's cohort of undergraduate students who volunteered their time.

Materials

Participants received seven lists of ten words each. We randomly selected the words from the Toronto Word Pool, a collection of English words commonly used in memory research (Friendly, Franklin, Hoffman, & Rubin, 1982). The distractor task for this delayed free recall task consisted of eight randomly created three-digit numbers.

Procedures

After participants provided basic demographic information and gave informed consent, they sat with a keyboard in front of a computer monitor located in a dimly lit room. The monitor, a *Tobii T120*, integrates an eye tracker into a 17-inch computer monitor (Tobii Technology, Stockholm, Sweden). The researcher calibrated the eye tracker before starting the experiment. In this delayed free recall task, common nouns were individually presented on the screen for 3 seconds each. After each list and before recall, participants engaged in a 16-second distractor task in which they saw three-digit numbers appear for 2 seconds each. Participants were required to sort those digits in ascending order out loud. After the distractor task, recall was initiated by three question marks (???). Participants had 45 seconds to recall, in any order, as many words from the current trial as possible. Without taking their eyes off the screen, participants typed their responses, pressing the "enter" key to record each response and clear the screen. Prior to the real lists, participants completed two practice lists with letters to become familiar with the task. Each participant's score consisted of the number of items recalled correctly, independent of recall position.

While participants engaged in the delayed free-recall task, pupil diameters were recorded for both eyes at 120 Hz using the eye tracker.

Pupil data was processed and analyzed using the *Tobii Studio* software (Tobii Technology, Stockholm, Sweden). Baseline pupil diameter was assessed prior to the experiment and prior to each trial. In addition, task-evoked pupillary responses were assessed as the difference between peak pupil dilation following stimulus onset and each trial's baseline pupil diameter. The entire experiment lasted approximately 20 minutes. Afterwards, participants were properly debriefed and, depending on recruitment method, received thanks for volunteering their time or class credit.

Results

Before analyzing the data, all blinks and artifacts were removed and replaced by using a linear interpolation algorithm. On average, as Table 1 shows, participants recalled 5 out of 10 words from each list ($SD = 1.67$), or 35 of the 70 words overall ($SD = 11.72$).

Table 1. Performance Scores: Words recalled accurately

	Min	Max	Mean	SD
Average per list (out of 10)	3.00	8.43	5.00	1.67
Average overall (out of 70)	21.00	59.00	35.00	11.72

We chose the left eye for data processing. We collapsed all pupil and serial position data across all lists and ran within-subject analyses. Pupil size fluctuated greatly between participants as the descriptive pupil data show (see Table 2).

Table 2. Pupil Size (mm)

	Min	Max	Mean	SD
Baseline	2.74	4.50	3.26	0.44
Encoding Phase	2.61	4.59	3.22	0.45
Recall Phase	2.90	4.70	3.40	0.45

The within-subjects repeated analysis of variance (ANOVA) revealed that the first item was significantly more likely to be recalled first over any other item, $F(9, 171) = 32.48, p < .001, \eta_2 = .63$ (see Fig. 1).

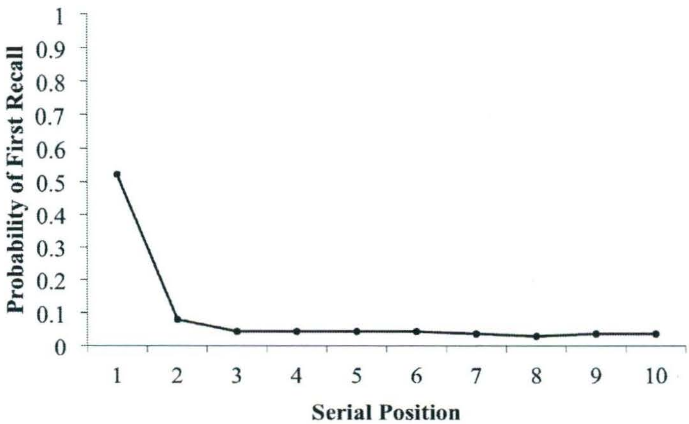

Figure 1. Probability of first recall. Congruent with existing research, the first word learned was likely to be the first item recalled.

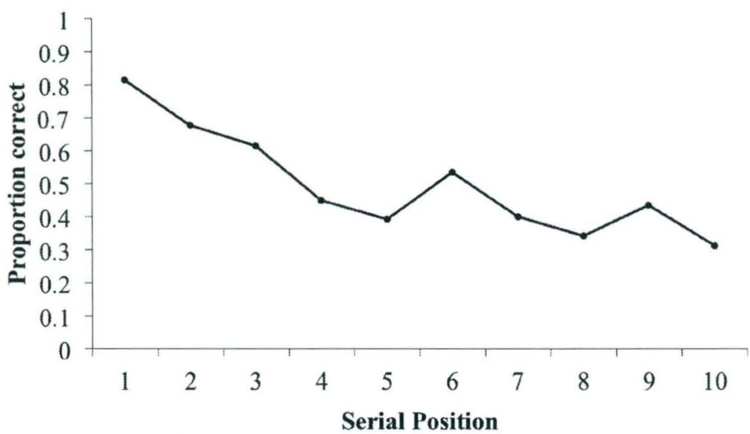

Figure 2. Accurate recall by serial position. Mean proportion correct recalled words as a function of serial position.

More importantly, the first item was also significantly more likely to be accurately recalled than any subsequent items, $F(9, 171) = 18.06$, $p < .001$, $\eta_2 = .49$ (see Fig. 2).

To investigate the pupil's role in the encoding and recall phase, we first analyzed the pupil response each word solicited by serial position. We found that the first item of each list corresponded to a higher pupil dilation than the other items, $F(9, 171) = 2.06$, $p < .05$, $\eta_2 = .10$ (see Fig. 3).

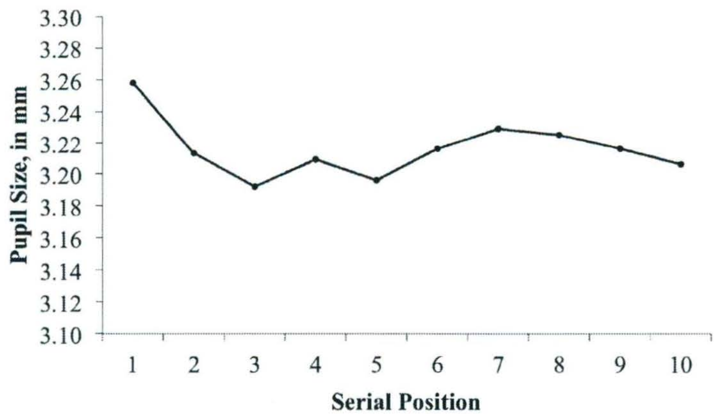

Figure 3. Pupil size during encoding. Mean pupil size as a function of serial position during encoding.

We investigated the pupil's behavior during the encoding phase by breaking down the 3 seconds each item was presented on the screen into 200 ms subintervals. Collapsing all single items, analysis revealed a distinct pattern of pupil behavior during the encoding phase, $F(14, 266) = 13.27$, $p < .001$, $\eta_2 = .41$ (see Fig. 4a). Specifically, pupil size initially decreased before increasing continuously during the entire encoding period. When considering each word individually, data analysis revealed that this general pattern fits with most items on the list except for the first item whose pattern will be investigated in future studies (see Fig. 4b).

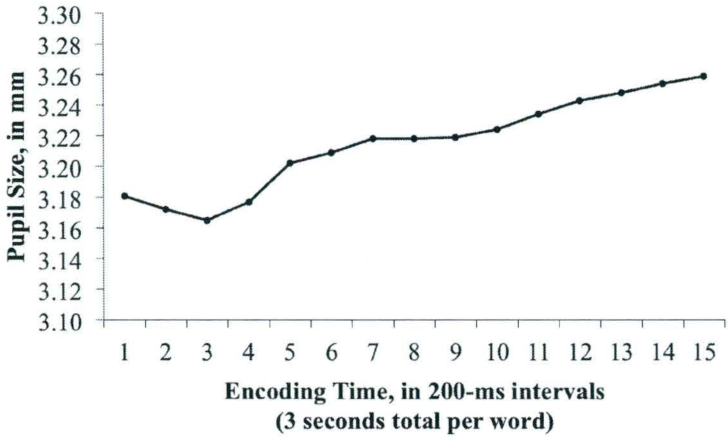

Figure 4a. Mean pupil size during single word encoding (means collapsed over all items). Pupil size is displayed as a function of encoding time, divided into 200-ms subintervals. Words were presented on screen for 3 seconds each.

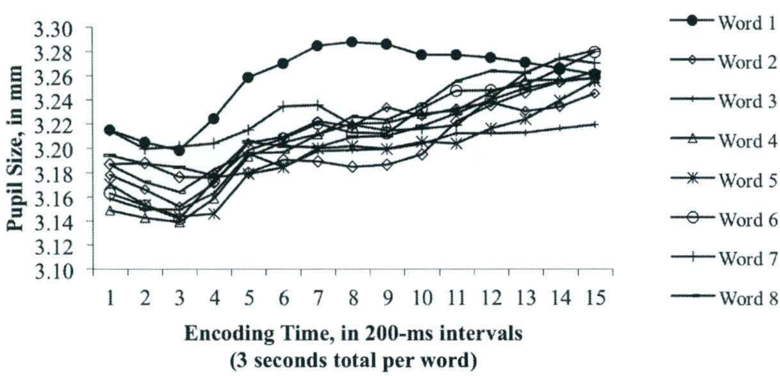

Figure 4b. Mean pupil size during encoding per each word. The pupil behavior is different for the first item when compared to all other items. Future studies will investigate this pattern further.

Turning our attention to the recall phase, we divided the 45-second recall phase into 2-second subintervals and collapsed all recall phases. A distinct pattern emerged for the pupil's behavior during the recall phase, $F(22, 418) = 17.27, p < .001, \eta_2 = .48$. Our data analysis revealed a sharp increase in pupil dilation at the beginning of the recall phase, the pupil remained large for some time before gradually decreasing over the 45-second recall period (see Fig. 5a).

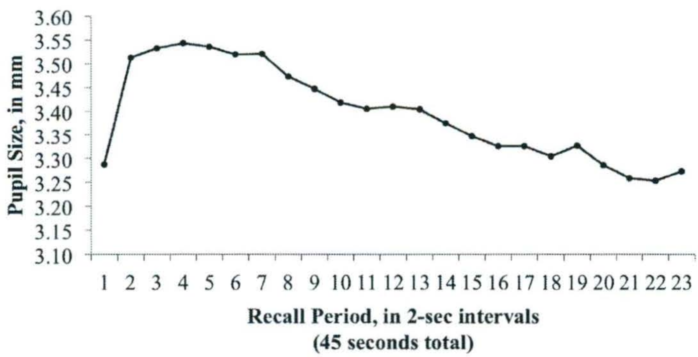

Figure 5a. Pupil size during recall. Pupil size during recall period as a function of time. The 45-second recall period is broken down into 2-second sub-intervals.

Interestingly, this pupil pattern was similar to the pattern of words recalled over recall time. The pattern of number of words recalled was also collapsed across all trials and revealed a significant result, $F(44, 836) = 10.24$, $p < .001$, $\eta_2 = .35$. Like the pupil, the number of words recalled peaks shortly after onset of the recall period and decreases thereafter (see Fig. 5b).

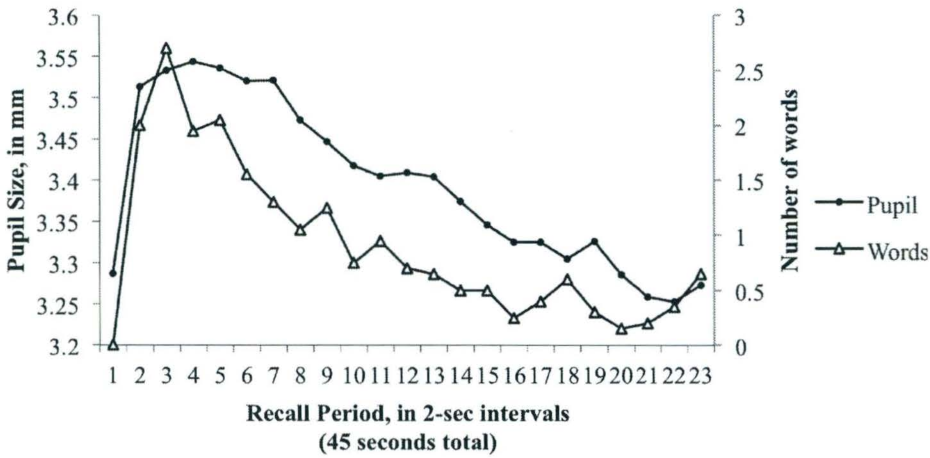

Figure 5b. Pupil size and number of words recalled. Mean number of words recalled as a function of time compared to pupil size during recall. Note: for ease of comparison, we converted the number of words recalled into a 2-second interval.

Discussion

For the first time, this study used a delayed free-recall task to investigate the role of pupil dilation in long-term memory. Our data analysis revealed known results by confirming primacy and probability of first recall effects. As expected, the participants were more likely to first recall the first item of each list. Likewise recall of the first item was overall more accurate than the recall of any other item. Previous research assumed this occurred because of the increased number of rehearsals the first item of a list receives (Rundus, 1971). We found, however, that the first item received more pupil dilation than subsequent items. Although rehearsal is clearly part of the process, a higher attention level at the beginning of the task also seems to be important. Participant attention peaked at the beginning of each list and decreased over the course of each trial. This pattern repeated over all trials to a diminishing degree. These findings appear to parallel results in immediate recall tasks that are consistent with primacy-gradient models (Page & Norris, 1998). In that context, the recall of items depends on the activation each item solicited. The item soliciting the greatest activation, in our case pupil dilation, was recalled first and then followed by the item of next greatest activation during learning. Perhaps participants simply try harder at the beginning of each trial or when the beginning of a new word list acts as a reset for attention. Future studies will have to investigate the successful recall of the first item in further detail.

For this exploratory study, we were most interested in the relationship between learning and retrieval behavior. The data reveal distinct patterns for both the encoding and recall periods. As participants began to learn each new word list, their pupils constricted slightly only to increase, gradually but continuously, over the course of each learning period. Although the rate of increase was more rapid at first, it slowed toward the end of the learning phase. Often participants rehearsed intensely, which could explain a continuous increase in pupil size as the rehearsal list became longer and longer. Independent of the strategy used to learn each list of words, committing items to memory in a rapid fashion became more effortful as the task progressed. Only a few items can be actively maintained in the working memory system. Once a participant was presented with more items than the temporary storage system could hold, typically between three and seven items at a time, he or she had to decide whether to spend resources on rehearsing earlier items or add new items to the rehearsal list. This decision required not only effort but also an increasing amount of attention, which in turn is reflected in pupil dilation.

Interestingly, the onset of recall revealed an even greater taxing of the memory system. With the onset of recall, participants' pupils dilated sharply, and remained dilated at a higher level before gradually decreasing to slightly below baseline. The rapid increase in pupil size may be attributed to an intense search effort, which many self-report studies have previously suggested. It is plausible to interpret the increase in pupil size as a search effort because the participants in our study had been distracted by another task before being able to recall the learned items. To our surprise, participants' pupil size was actually larger at the onset of recall than at the end of the encoding phase, indicating that search processes are much more effortful than learning itself. Although good memory recall is related to the efficient storage of memories, for example by using elaboration on existing knowledge, it seems to be more important to generate the correct retrieval cues to access those memories. In a delayed free-recall task such as ours, participants had to generate their own retrieval cues, an element that requires a fair amount of cognitive resources, as indicated by a larger pupil size.

Overall, we had hypothesized that pupil dilation during learning would be indicative of recall behavior, a pattern that became apparent when comparing pupil behavior to the number of words recalled over time. It appears that pupil dilation closely mirrors recall behavior, for the pupil increased sharply after onset of the recall period. Maximum pupil dilation at first coincided with the number of words recalled. Participants recalled more words early on, as is typical in memory research. More interestingly, however, the pupil decreases in a comparable fashion with the numbers of words recalled. As the pupil size decreases, fewer words are recalled, perhaps indicating a decrease in the intensity of a participant's search effort. Future studies need to investigate in more detail how the pupil dilation during encoding is related to the pupil dilation during recall. Does a high pupillary response predict earlier or more accurate recall later? Does successful recall demand a high level of attention? Understanding how we divide and maintain attention will ultimately help us understand memory and attention failures and cognitive deficits typical in ADHD and other attention disorders.

Because of the exploratory nature of this study, a follow-up study is warranted to reveal possible systematic individual differences between high- and low-scoring individuals. It remains unknown if a higher pupillary response is predictive of the quality of encoding. Additionally, it would be interesting to examine the inter-word response time and pupil behavior during the recall phase to explore further the controlled search processes between each word.

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