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Does retrieval require effort? Effects of memory strength on pupil dilation.

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Abstract

The current study investigates the relation between retrieval effort and the relative memory strength of mentally stored information. A previous pupillary study by Magliero (1983) showed that encoding effort reacts to the recency effect but no studies have linked effort as measured by pupillary dilation to the frequency effect. In the current study, phasic pupil dilation of 15 participants was measured and analyzed during retrieval tasks while they were learning topographical facts. The facts were studied once and tested during four repetitions in one of two repetition-interval conditions. We hypothesized that retrieval effort will decrease as the relative strength of a memory trace increases. This hypothesis accounts for recency effects as well as for frequency effects. Analysis of the phasic pupil response in the experiment shows a significant main effect for the repetition interval condition. Furthermore an interaction effect between the number of repetitions and repetition interval was found, indicating that the difference in effort between short and long repetition intervals decreased as the number of rehearsals increased. These findings largely confirm our hypotheses and the assumptions of theories that assume that increased retrieval effort increases learning gains.

Keywords: Memory; Effort; Retrieval; Pupil; Dilation; Learning; Rehearsal.

Introduction

Ever since Ebbinghaus (1885) it is known that recall performance decreases over time, irrespective of whether performance is measured as retrieval latency or accuracy. Over the years, many different theories have been proposed to explain this effect (Byrnes, 2000). Regardless of the proposed underlying mechanisms, all theories assume that the relative memory strength of an item decreases over time. Furthermore, all theories assume that rehearsing the materials can counter this decrease as the rehearsals increase the relative memory strength, resulting in faster and more accurate responses. However, whether these changes are also reflected in the effort it takes to retrieve information is still an open question. The study reported in this paper used pupil dilation to investigate the relationship between effort and relative memory strength.

Earlier work that associated memory strength with pupil dilation is the study reported by Magliero (1983). In his experiments pupil dilation was measured during an encoding task. Participants were presented a list of words and some of these words were repeated 1 or 2 times with either 0, 1, 4 or 8 intervening words. During the whole encoding phase pupil dilation was recorded. Magliero compared the pupil dilation on the first presentation with the pupil dilation on subsequent presentations. His results showed that pupil dilation was decreased if there were one or zero intervening words, but dilation increased again for four or eight intervening words. These results indicate that encoding effort is decreased when recently encoded information is repeated, in line with the idea that recently encoded information is stronger represented in memory.

Although Magliero's results indicate that there is a link between memory strength and effort, the participants in this study were not explicitly instructed to learn the words in the list; the participants were told at the start of the experiment that they would participate in a memory task after the list of words was presented. The current study was set up to test the effects of memory strength on pupil dilation during the retrieval process. As relative memory strength is assumed to decrease over time and increase with the number of rehearsals, we will manipulate both the number of intervening items (and thus the time between repetitions) and the number of repetitions of a to-be-learned item.

Decay, Interference, Associations and Rehearsal

Different theories propose different mechanisms underlying the dynamics of memory strength. One of the more constant mechanisms is the notion that rehearsals strengthen memory traces, which increase retrieval performance. A neuronal explanation of the beneficial effect of rehearsing was proposed by Hebb (1949), who stated that neurons strengthen their connection when they show repeated temporal electrical activation. More support for the beneficial effect of rehearsing was found in studies that showed that recall performance decreased when rehearsal was prevented (e.g., Brown, 1958; Peterson & Peterson 1959). Since these initial findings, many memory models have been proposed to explain the constructs of human memory such as the modal model by Atkinson & Shiffrin (1968) and the multi-component model (Baddeley and Hitch, 1974; Baddeley, 2009). Both these models incorporate the importance of rehearsing and assume that non-rehearsed items will drop out of short-term memory. However, neither model provides a detailed account of this process.

More recent theories are more explicit about how information becomes less accessible. Decay based models (e.g., ACT-R, Anderson et al, 1998) assume that information becomes less accessible as a function of time, whereas other models assume that the interaction with other information causes the decreased performance (e.g, association-based models, SAM, Raaijmakers, 2003; and interference-based models, such as SOB, Farrell & Lewandowsky, 2002). This decrease in performance has to be countered by rehearsals. Rehearsal either strengthens a memory trace by increasing the activation of an information chunk (i.e., the strength in memory; ACT-R), by creating and strengthening associative connections between cues and information (SAM), or by adjusting the vector weights of the new and all other learned information (SOB).

Therefore, regardless of the underlying mechanisms, all theories account for recency and frequency effects by means of relative memory strength.

Relative Memory Strength, Pupil Dilation and Effort

The time to retrieve mentally stored information increases when the relative strength of this information decreases (e.g., Sternberg, 1969; Stanners et al., 1969; Jolicœur & Dell'Acqua, 1998). Although equating longer retrieval times with increased effort might seem straightforward, Porter, Troscianko and Gilchrist (2007) have shown effects of effort on pupil dilation in tasks that were matched for reaction time.

Although changes in pupil size as a response to mental activities was actively studied from the late 19th century on (e.g., Schiff and Fao, 1874, Heinrich, 1896?), renewed interest in this measure stems from the early 1960s (e.g., Hess & Polt, 1964). In 1966, Kahneman and Beatty conducted an experiment in which participants had to memorize a list of items and later report it. As the pupil dilation increased with each additional presentation, and decreased after each successful report, this study is taken as a prime example of the link between pupil dilation and effort. After these initial findings, numerous studies (involving memory, language processing, complex reasoning, perception and attention) indicated that pupil dilation increases as a response to increased mental effort in various tasks (for a review see Beatty, 1982).

Because the study by Porter et al (2007) showed that effort effects are not always reflected in reaction times, it remains unclear whether the effort involved in retrieving mentally stored information is also influenced by relative memory strength.

We hypothesize that less effort is needed to retrieve mentally stored information when the relative strength of the information increases. To test this hypothesis an experiment was performed in which participants had to learn facts. To investigate the recency and rehearsal effects independently, the facts were repeatedly tested at two different repetition intervals. We predicted that (1) an increased number of repetitions would result in a decreased dilation of the pupil; (2) a longer time between two repetitions will result in a increased dilation. Both these predictions are based on the notion that increased relative memory strength is reflected in lower effort as estimated by pupil dilation. With respect to the interaction, if effort is linked to relative memory strength in a similar way as retrieval latency, an interaction is to be expected in that the decrease of dilation is stronger in the more difficult condition.

Method

Participants–Seven male and twelve female students of the University of Groningen volunteered to participate in this experiment in exchange for study credits. Informed consent, as approved by the Ethical Committee Psychology of the University of Groningen, was obtained before testing. All participants were naïve to the study material.

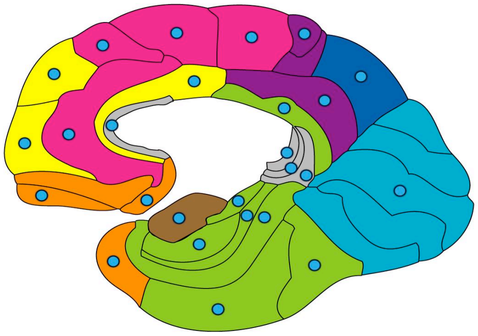

Figure 1: Display as presented to the participants during the answer-part of a test-trial. Circles mark the 26 areas used in this study.

Stimuli–Participants had to learn brain topography. The cross-section of the brain used in this experiment is shown in Figure 1. A total of 26 areas were presented, indicated by the 26 circles shown. The areas largely correspond to Brodmann areas, although some Brodmann areas were combined into a single aggregate. Each of the areas was indicated throughout the experiment by its topographical full name (e.g., "Inferior Temporal Gyrus", or "Dorsal Anterior Cingulate Cortex"). Two types of trials were presented, study trials and test trials. During the study trials, the name of the to be identified area was shown above the cross-section in Courier New 26 point font, and the corresponding area was indicated by an arrow. During a test trial, participants were first presented the name of a previously learned area in Courier New 26 point font in black on a white background, centered on the screen. After this presentation, the cross-section as shown in Figure 1 was shown. Participants indicated which area they thought corresponded to the presented name by clicking on one of the 26 circles.

Design–Every participant was presented all 26 areas, randomly distributed over five learning blocks. Three learning blocks contained four areas each, and two learning blocks contained seven areas. Every block was presented five times, in consecutive runs, before the next block commenced. All items of a block were presented in each run. The first run consisted of study trials; the four subsequent runs of test trials. When a run was completed, the order of areas within that block was randomized to avoid learning the areas in a fixed order, while taking care that an area was never presented twice in a row.

As the repetitions of each block were presented consecutively, the average time or distance between two presentations of the same area is a function of the number of items in a block. The four area-blocks constitute the short repetition interval condition, and two seven area-blocks constitute the long repetition interval conditions. Because the order of areas within each run was randomized, the interval between two repetitions of same area in the short repetition interval blocks was one to six areas. For the long blocks the repetition interval was one to twelve intervening areas. The first block was a short repetition interval block, and subsequent blocks alternated between long and short repetition interval (i.e., S, L, S, L, S). A total of 130 trials were presented.

Procedure–Participants were seated in front of a 22” (20” viewable) IIlyama Vision Master Pro 513 CRT monitor (set at a resolution of 1280 x 1024) and were asked to rest their chin on a head mount in front of the screen. Distance from head mount to the screen was approximately 60 cm. Pupil dilation of the right eye was measured at 500 Hz using a SR Research EyeLink 1000 eye tracker which was placed immediately below the computer screen. Presentation of all stimuli was controlled using PsychToolBox (Brainard, 1997; Kleiner et al, 2007) with the Eyelink extensions (Cornelissen et al, 2002).

Participants were instructed that they were to learn brain topography, and that they would get a set of study trials that presented the areas and the associated names, followed by four runs of test trials in which they had to indicate the answer by clicking on the circle of the correct region. All instructions were presented on-screen.

A study trial started with the string “Study trial…” presented centered on the screen for three seconds after which the study screen appeared. This screen showed an area name together with an arrow that indicated the right corresponding position. Although the right answer was indicated, the participant was still free to choose any desired answer. After the participant clicked on a circle to indicate his or her answer, feedback was provided. The selected circle turned green for 1 second if correct, or red for 2 seconds if incorrect. If an incorrect answer was given, an arrow highlighted the correct area.

A test trial started with a fixation cross that was presented centered on the screen for 4 seconds, followed by the presentation of the area name for 6 seconds. After this period, the cross-section of the brain was presented. The participant had 10 seconds to provide an answer by clicking on a circle associated with an area using a standard computer mouse. Feedback was identical to the feedback presented during the study trials.

The slow pace of the experiment allowed for accurately measuring the relatively slow fluctuations in pupil dilation. The long presentation of the fixation cross at the start of each test trial provided the baseline to which later measures were scaled. The long presentation of the area name allowed for measuring a complete phasic pupil response.

The complete experiment, including setup and debriefing, lasted about 25 minutes.

Results

Four participants were excluded because of technical measuring problems or not following instructions. The data from 15 participants (5 male; average age 21.5 years; SD = 2.01) were used for further analysis. The first short repetition interval block was considered training, and was not analyzed. We will report data of Run 2 to 5 for Blocks 2 to 5, as in Run 1 only study trials were presented. We will refer to these runs as Repetition 1 to 4. All trials with a response time longer than 8 s or shorter than 500 ms were considered outliers, and removed from further analyses (.9% of all trials).

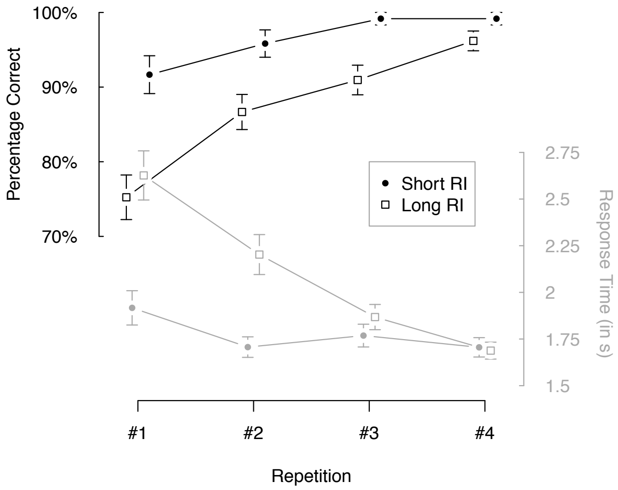

Figure 2: Percentage Correct and Response Time data for Short and Long Repetition Intervals. The error bars represent one standard error.

Behavioral Results Figure 2 shows the main behavioral data. The two lines in black indicate the percentage correct responses over the four repetitions, which were submitted to a repeated measure ANOVA after an arcsine transform. As expected, the correctness is higher for the short repetition interval condition (F(1,14)=26.8, η_p^2=.66, p<0.001) and increases with increased number of repetitions (F(1,14)=24.4, η_p^2=.64, p<0.001). The figure also shows that the advantage of the short repetition interval condition decreases over time (F(1,74)=7.1, η_p^2=.09, p=0.009).

An inverse, but qualitatively similar pattern of results can be observed for the response times, with main effects for condition (long repetition intervals result in increased response times, F(1,14)=16.9, η_p^2=.55, p=0.001) and repetition (responses decrease with increased number of repetitions, F(1,14)=26.7, η_p^2=.66, p<0.001). As for the percentage correct data, the initial response time advantage for the short repetition interval blocks decreases with repetitions (F(1,74)=38.2, η_p^2 =.34, p<0.001). These results are in line with previous studies: longer repetition intervals are associated with lower performance than shorter repetition intervals, and an increasing the number of repetitions improves performance with a stronger effect for the long repetition condition.

Pupillary Results The pupil diameter as reported by the SR Research Eyelink 1000 eye tracker was cleaned from saccade and eye blink induced artifacts by linear interpolation of 25 samples before and after a saccade, and 50 samples before and after a blink. Any remaining artifacts were manually selected and the associated dilation was replaced by linear interpolation. A total of 58 trials (3.9%) were excluded because of either too fast or slow responses or too many artifacts. The development of the relative dilation during the presentation of the area name for the first and last repetition is plotted for the short and long repetition intervals separately in Figure 3.

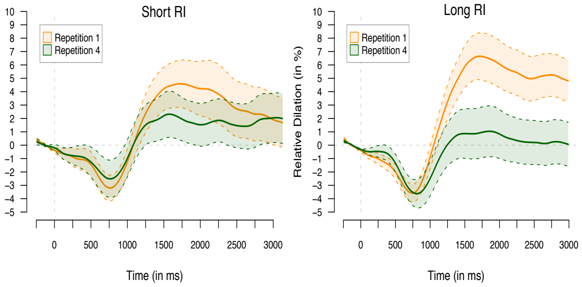

Figure 3: Lowess filtered (*f*=.05) relative dilation for first and last repetition, plotted for short (left) and long (right) retention intervals (RI). Zero ms is the onset of the screen. The dashed lines indicate one standard error of the means.

The phasic pupil response was calculated per trial as the difference in dilation between the constriction and peak (see, e.g., Bradley, Miccoli, Escrig & Lang, 2008). For both estimates, the average of a window of 400 ms around the extreme was calculated. Mean phasic pupil response and (between-subject ANOVA-type) standard errors are depicted in Figure 4 for all conditions. As the resulting distribution was heavily right skewed (Shapiro-Wilk test: W=0.88, p<0.001), the data were log-transformed (W=0.99, p>.9). Nine (.07%) outliers (> 2.5 SD) were removed.

We tested the effects of repetition interval and number of repetitions on phasic pupil response in correct trials using linear mixed effect models (Baayen, Davidson, Bates, 2008) with crossed, independent random effects. Repetition interval and number of repetitions were entered as fixed factors, whereas area and participant were entered as random factors[1].

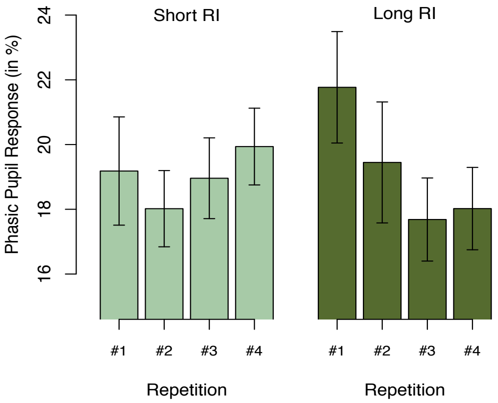

Figure 4: Phasic pupil response (in %) for the short (left) and long (right) repetition intervals per repetition. The error bars represent one standard error of the means.

Table 1 shows the results of this analysis. In line with the hypotheses, the analysis shows that the long retention interval is associated with increased pupil dilation (β=.14). This effect is mainly caused by the first repetition as the interaction effect decreases the difference between short and long repetition interval with .06 for each additional repetition. Post-hoc analyses indicated that the interaction was indeed caused by the decrease in dilation in the long repetition interval (β=-0.05, p<0.001) and a lack of repetition effect in the short repetition interval condition (β=0.02, p=0.393).

Table 1: Overview of the estimates (β), the upper and lower 95% Bayesian highest posterior density (HPD) confidence intervals, and p-values based on the MCMC posterior distribution (determined using pvals.fnc with 10000 samples, Baayen, 2008) of the fixed factors entered in linear mixed-effect model.

Fixed Effects				
		HPD95		
	β	lower	upper	p_{MCMC}
Intercept	2.81	2.67	2.97	<.001***
Repetition Interval	0.14	0.02	0.27	.024*
Repetition Number	0.01	-0.02	0.05	.424
RI x RN	-0.06	-0.11	-0.02	.006**

Discussion

We conducted an experiment in which pupil dilation was measured to assess effort during fact learning. We predicted a reverse relation between relative memory strength and effort. To test this hypothesis, we manipulated relative memory strength by repeating all information multiple times at one of two repetition intervals. The behavioral results of the experiment indicate that our manipulations were successful: performance increased with increased repetitions

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[1] We also fitted more complex models, including, for example, trial number and block. As these models did not qualitatively change the outcomes, we decided against reporting the more complex models here.

and decreased when the repetition interval was longer, an effect that diminished with increased repetitions. These effects are in line with the assumption that repeated presentations increase relative memory strength and an increased interval between two repetitions results in a decreased memory strength (compared to a shorter interval).

Although slightly different, the pupil dilation effects also indicate effects of relative memory strength. First of all, the long repetition interval – in which a lower relative memory strength is assumed – is associated with increased pupil dilation. Second, the interaction between repetition interval and number of repetitions indicates that the pupil dilation decreases with an increased number of repetitions in the long repetition interval condition. Both these effects argue in favor of an effect of relative memory strength on effort. However, we also predicted an effect of the number of repetitions in the short repetition interval conditions, which could not be found. There are multiple explanations possible for the lack of an effect in this condition. One explanation is that the short repetition interval condition resulted in very strong memory traces that were retrieved in a fraction of the time available to the participants. After retrieving the fact, participants might have involved in other mental activities, which artificially raised the measured pupil dilation. Another possible explanation is that the phasic pupil response as shown in Figure 4 has a floor effect of around 18% in our setup. This response could, for example, reflect the effort associated with reading and processing the presented area name. If these components of the process already invoke a large pupillary response, small effects during high levels of relative memory strength are difficult to identify. To summarize, these data indicate a negative correlation between relative memory strength and mental effort.

Our findings can be explained by the leading memory theories. According to these theories, introduced above, the measured increases in retrieval can be explained by extra memory decay after longer repetition intervals (ACT-R), weakening of associative connections between cues and mentally stored information (SAM) or greater interference from the additional stimuli in the long repetition interval (SOB).

Porter et al (2007) indicated that effort effects are not always captured during the retrieval process. However, the effects from the current experiment are in line with previous response time memory studies that were able to find these effort effects. By using pupil dilation as an additional measure of effort, our study gives a stronger indication that manipulations in repetitions and repetition intervals affect retrieval effort (e.g., Sternberg, 1969; Stanners et al., 1969; Jolicœur & Dell'Acqua, 1998). Furthermore, the finding that retrieval effort is higher for facts with a lower relative strength is in line with a fMRI study by Buckner, Koutstaal, Schacter, Wagner, and Rosen (1998). They conducted a word recognition task and found that during a successful retrieval of shallow encoded words, activation in the bilateral anterior insular regions and a left dorsal prefrontal region increased. Buckner et al. argue that this increased activation is indicative of increased effort. Thus, the current study extends these and Magliero's (1983) findings by focusing on retrieval effort instead of on encoding or recognition effort.

Although memory theories can explain our findings, it still remains unclear what biological mechanism exactly causes the increased retrieval effort. A number of recent theories on the causes of pupillary effects might help in unraveling this question. One explanation for the pupil response to mental effort can be derived from the Adaptive Gain Theory, which states that activation in the cortex is strongly dependent on the Locus Coeruleus (LC), a nucleus in the brainstem regulating arousal and behavior (Aston-Jones & Cohen, 2005). A high correlation between activation in the LC and pupil dilation was found in monkeys, and later the effect was confirmed in humans (Rajkowski et al, 1994; Gilzenrat et al, 2010). By linking effort during memory retrieval via pupil dilation with activation in specific brain regions, more precise hypotheses can be formulated.

Regardless of the underling mechanisms, the results of the current study can have an extensive impact on learning theories. Many studies have shown the beneficial effect of deeper encoding on later retention, whether it is by an implicit learning task or by mnemonics (Krinsky & Nelson, 1981; McDaniel et al, 1986; Byrnes, 2000). According to the retrieval effort hypothesis by Pyc and Rawson (2009), this effect is partly dependent on the amount of effort required, also during successful retrievals. Although they confirmed their hypothesis by manipulating retrieval difficulty through changes in repetition interval and the number of repetitions, they did not test whether effort was indeed increased. The current study confirmed this assumption by showing that pupil dilation decreases when the repetition interval decreases and when the number of repetitions increase.

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