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COGNITIVE EFFORT AND PUPIL DILATION IN CONTROLLED AND AUTOMATIC PROCESSES

Abstract

The Five Digits Test (FDT) is a Stroop paradigm test that aims to evaluate executive functions. It is composed of four parts, two of which are related to automatic and two of which are related to controlled processes. It is known that pupillary diameter increases as the task's cognitive demand increases. In the present study, we evaluated whether the pupillary diameter could distinguish cognitive effort between automated and controlled cognitive processing during the FDT as the task progressed. As a control task, we used a simple reading paradigm with a similar visual aspect as the FDT. We then divided each of the four parts into two blocks in order to evaluate the differences between the first and second half of the task. Results indicated that, compared to a control task, the FDT required higher cognitive effort for each consecutive part. Moreover, the first half of every part of the FDT induced dilation more than the second. The differences in pupil dilation during the first half of the four FDT parts were statistically significant between the parts 2 and 4 (p=0.023), and between the parts 3 and 4 (p=0.006). These results provide further evidence that cognitive effort and pupil diameter can distinguish controlled from automatic processes.

Keywords

• Pupillary diameter • Executive functions • Psychological evaluation • Cognitive effort • Neuropsychology • Five digits test

Introduction

Dissociation between controlled and automatic cognitive processes is well established in various fields of knowledge, such as neuroscience [1], cognitive psychology [2], and behavioral economics [3]. The dual-process theory states that controlled and automatic processes interact in daily activities. The automatic processes provide fast responses and interpretation to environmental stimulus. In theory, these responses are implicit and unconscious and, from a neurobiological point of view, related to subcortical structures such as those present in the extended amygdala, posterior cortical and subcortical regions [4]. On the other hand, controlled processes are conscious, explicit, focused on analytical and deliberative processing, and related to the neurobiological substrate of the frontostriatal network [4].

In daily life, many cognitive processes are performed automatically, for example: recognizing a familiar alphabetic symbol, solving a simple arithmetic operation, conducting a simple conversation or recognizing a small number of objects [5]. Similar models for automatized processes are also relevant for the understanding of reasoning, judgment and social cognition [6].

Executive functions are controlled cognitive processes related to goal-directed behavior. Although there is no consensual model of these functions structure and organization, several studies sustain a hierarchical perspective where more basic executive functions associated with cognitive flexibility (such as inhibitory control and working memory), can result in more complex aspects of executive functions, such as planning and problem-solving (see [7] for a review). Executive functions act as an integrative cognitive function, associating different cognitive domains and processes with the solving of complex cognitive tasks [7]. They are largely superimposed with the concept of intelligence in terms of psychometric and neuroimaging data [8].

The study of the dissociation between controlled and automatic processes has involved the association between cognitive effort and physiological parameters. For example, pupillary diameter can be used as a physiological marker that provides real time information about cognitive effort demanded by a cognitive task. As shown by Kahneman and Beatty [9], pupillary diameter increases with the amount of information loaded into working memory. The pupillary diameter was also studied in different contexts, such as sentence processing [10], attention [11], arithmetic processing [12], and inhibitory control [13]. Integrating this physiological measure in neuropsychological assessment could provide data that are more accurate regarding the nature of processes underlying the task. Its main advantages are the real time measurements of the cognitive effort, a considerably low cost [14], and independence of conscious control [15].

The Five Digits Test (FDT) is a neuropsychological test that aims to assess automatic and controlled cognitive processes [16]. This test is composed of four consecutive parts with increasing difficulty level, the first two of which evaluate automatic processes and the last two of which evaluate controlled processes. The subject must attain cognitive effort in order to score well in this test. The present study aims to evaluate whether the pupillary diameter can distinguish automated and controlled cognitive processing during the FDT and whether this effort decreases in the course of each of the tests' four parts.

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Procedures

Participants

The participants were 21 (eleven women and 10 men) healthy Brazilian college students aged from 16 to 32 years (mean = 21.3 ± 4.3 years). The subjects were recruited by local announcements and performed the neuropsychological tests in an artificial environment (a quiet room with controlled lightning and ambient noise). The study was approved by the local ethics board (registered under the number 12344813.0.0000.5149).

Pupillary measurements

The pupillary diameter was recorded by the SMI Eye Tracking Glasses® (SensoMotoric Instruments GmbH, Teltow, Germany). This device has a sampling rate of 30 Hz, a 1280 x 960 pixel resolution scene camera, and operates with an infrared light and a video camera that provides video output at 24 frames per second. SMI's proprietary software, BeGaze 3.2, was used in order to export pupil diameter in millimeters. As the eye tracker recorded footage of the task, it was possible to record behavioral data and analyze it later. Thereby, it was also possible to determine the exact time when the test started and ended, thus avoiding possible mistakes done by the examiner.

Assessment of automatic and controlled processes

Cognitive performance was evaluated through the FDT [16]. This test is a number-quantity adaptation of the Stroop Color Word test, which only requires the subject to know the first five Arabic numerals and their respective symbols (1, 2, 3, 4 and 5), therefore, it is less susceptible to effects from formal education. It is composed of four parts of increasing difficulty, with 50 stimuli, presented each in an A4 paper. These four parts can be categorized into automatic or controlled processes. The subject must answer each one of them as fast as possible.

Automatic processes: these are represented by the first two parts of the test. In these two parts, the examinee must name each stimulus as fast as possible; these parts are related to processing speed. Part 1 (also called Decoding), requires the examinee to read as quickly as possible the digit each box contains; these digits are compatible with the quantity of digits presented, for example: 2-2, must read "two", for a better understanding see (Fig. 1). Part 2 (Retrieving), is composed of asterisks (stars) with varying quantities (1 to 5); in this part the amount of asterisks (stars) must be counted (i.e.: ***, "three"").

Controlled processes: represented by the last two parts of the test, and related to executive functions such as inhibitory control and cognitive flexibility. Part III (Inhibiting) introduces the Stroop effect to the test. Here, the stimuli are in an incongruent scenario, where the boxes present groups of digits that do not correspond to their arithmetic value, and the examinee must count how many digits are in each stimulus (i.e.: "2-2-2-2", correct answer: "four"). The last part (Shifting) is similar to the previous, with a new rule which adds the flexibility component to the test: some stimuli are highlighted, in these, the examinee must shift the rule, and instead of counting the amount of numbers, the examinee must read the algorism (i.e.: "4-4-4" must now be answered as "four" instead of "three").

The test was applied by using the formal instructions provided by the manual [17]. To assure the test's comprehension, a training session (10 stimuli) was performed for every part of the test. The subject was instructed to start the test when commanded. At that time, the examiner started recording pupillary data on the eye tracker computer. After the subject finished giving the last answer to the stimulus the data recording was stopped manually. The FDT scores relate to the time taken to complete each part, which provides the index of "speed", and the errors committed provide the index of "accuracy, or efficiency". The measurement of time to complete this part was equal to the length of the pupillary data recording. Previous studies suggest a good validity of the FDT for the Brazilian population [18, 19].

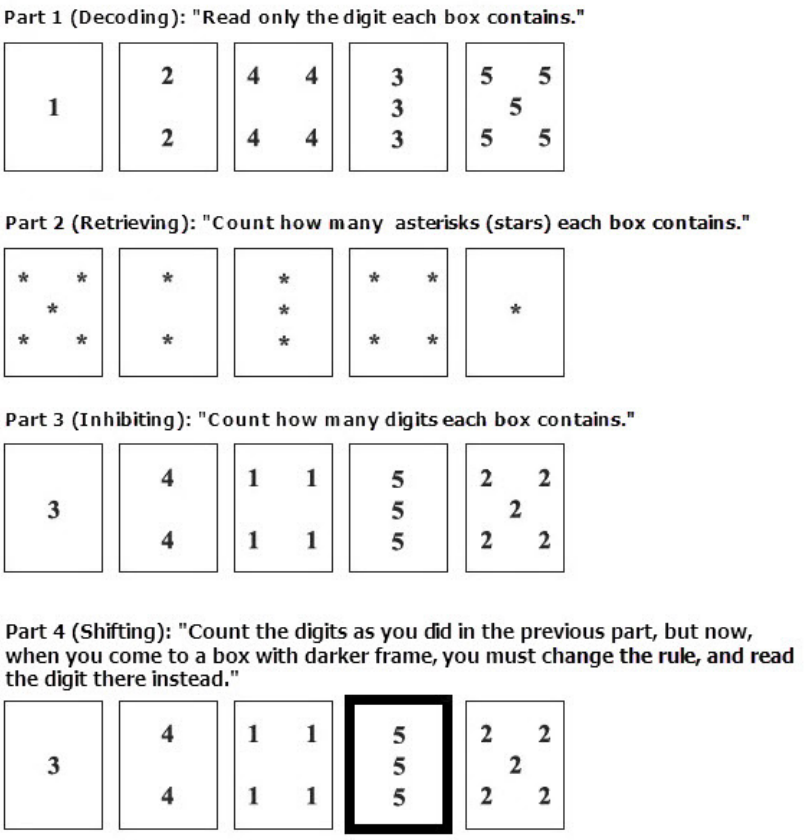

Figure 1. The Five Digits Test. The test is composed of four parts; each of these parts is composed of a series of 50 boxes that contain stimuli similar to those presented.

As suggested by Gabay [20], it is possible to control pupillary changes induced by different lighting conditions by establishing a baseline, which preserves visual properties from the original test. Therefore, a control task was performed at the beginning of each of the FDT parts. This task simulated the visual appearance of the FDT while exchanging the stimuli for letters (Fig. 2). The examinee was then required to read the letters as if he/she was reading a text. Substantial pupillary dilation in this test is not expected as there is no effort associated with an already automatized task (reading letters at a usual reading speed) rather than novel ones (reading visually new stimuli as fast as possible) [21]. Thus, this control task should evoke little cognitive effort. To summarize: the modified FDT was composed of eight parts, four of them being the control parts and four test parts.

Procedure

The experiment was conducted in a room with a controlled and constant lighting setting during the entire study. The setup ensured that each participant felt comfortable with the eye tracker glasses. Calibration was performed triangularly through three dots printed on an A4 paper sheet. Participants were instructed to keep their head approximately 40 cm away from the test. Before the instructions were given, two minutes were set aside so that the subject could get comfortable in the evaluation room. Then, at the beginning of every FDT, the examiner gave instructions for the control task. After each control task, the FDT instruction was given for each specific part (see Fig. 1 for a brief presentation of each instruction) and training was performed. Before the test began, the examiner emphasized that the examinee had to read the stimuli as fast as they could.

Data analysis

The pupillary diameter was calculated by using the average of both pupils' diameters data collected in the entire FDT (50 stimuli each part). When calculating the mean pupillary diameter, values equal to zero, below 1 mm or above 6 mm were excluded from the sample. These values were considered either as blinks or as artifacts. The subject's performance during the FDT was calculated using the amount of time required to complete the test and the number of errors present. Descriptive statistics were used for demographic data. The Kolmogorov-Smirnov test was used to characterize the distribution of the time to complete the task, errors committed, and pupillary diameter. The repeated measures ANOVA was used to compare differences between data from each FDT part. Spearman's correlation was used to explore associations between pupillary and behavioral data. Statistical significance was defined at p values less than 0.05. In order to control for habituation effects, a second analysis tested each of the FDT parts divided into two blocks (the first 25 and the last 25 stimuli). The test's author, Sedó [17] suggested this division in the original manual as a measure of habituation. The second block should be performed faster than the first, since the interference effect is smaller in the final items when compared to the first-part items [22]. Therefore, the mean pupillary diameter was calculated for each block (1 and 2) of the four test parts and analyzed through the repeated measures ANOVA. In order to minimize possible type I errors, the Bonferroni correction was used.

Results and discussion

Five Digits Test: behavioral data

The repeated measures ANOVA showed significant differences when comparing the measured "time" between each of the four FDT parts ($p < 0.000$), except between the part 1 and the part 2, supporting a previous finding that the time needed to complete the FDT parts is longer for to the controlled (cognitive) parts (3 and 4) [17]. No significant differences were found when comparing the amount of errors made during the task ($p > 0.05$). This can be explained by the educational level of the population studied: most were undergraduate students. For this reason no errors were expected in parts 1 and 2 (automatic processes), and also just a few errors were expected in parts 3 and 4 (controlled processes). This led to a low variability in the data obtained.

Analysis of pupillary data

The Spearman rank-order correlation showed no effect between the behavioral data (number of errors, or response efficiency) or time to complete task (processing speed) and the mean pupillary dilation in its correspondent FDT part ($p > 0.05$), and no correlation of the mean pupillary between each of the FDT parts ($p > 0.05$). To analyze the pupillary data of all the FDT parts, the t-test for repeated samples was performed. Every part of the test stage showed significantly higher mean pupillary diameter than the corresponding control stage ($p < 0.00$), except for part 2 (Retrieving) ($M = 3.01$, $SD = 0.676$) and its respective control stage ($M = 3.410$, $SD = 0.669$) pair; $t(20) = -1.462$, $p = 0.149$.

No significant differences among the mean pupillary diameter for all FDT parts were found through the repeated measures ANOVA, $F_{1.68,\ 33.61} = 1.876$, $p = 0.174$. Each of these four parts was then re-sampled into two blocks. The first 25 stimuli were considered as the first block and the last 25 were considered as the second block. The t-test for repeated samples revealed that, for every part of FDT, the mean pupillary diameter was higher in the first block ($p < 0.001$). A similar effect was found when this analysis was performed on all control stages

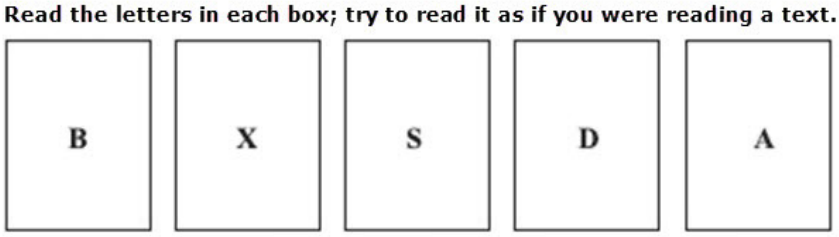

Figure 2. The control task. This task simulated the appearance of the Five Digits Test. This task was applied between each of the FDT parts.

($p < 0.000$). When considering the first block of the FDT, the repeated samples t-test (Table 1) showed significant differences between parts two and four ($p = 0.023$) and three and four ($p = 0.006$). No significant differences were found when the same analysis was performed either for the second block or the control stages.

Discussion

The present study assessed the hypothesis that the dissociation between controlled and automatic cognitive processes could be observed through pupillary dilation. All control tasks showed smaller pupillary dilation when compared to their corresponding test stage. These results support the assumption that the FDT requires greater cognitive resources than reading known letters at the usual reading speed, supporting the assumption that the act of speeding up the process of reading may demand high cognitive effort. Previous findings established that there was an increased time to complete the task in FDT. For example Paula *et al.* [19] examined a sample of elderly subjects and found that there was a greater increase in the time required to complete an FDT part was higher in the controlled parts (from 3 to 4) than in the automatic parts (from 1 to 2). In the present study, a greater increase in the time required to complete an FDT part was confirmed and followed by the increased pupil diameter, but significant differences were found only between the first block of the controlled parts.

Moreover, as the overall mean pupillary diameter from both automatized parts of the FDT was smaller than for the controlled parts of the FDT, the pupil diameter may provide physiological data to identify and discriminate effortful cognitive processes from those that do not require effort. The findings of Steenbergen and Band [23] corroborate this hypothesis, as they found pupil dilation most likely reflects conflict processing, which may indicate a need for additional cognitive control.

It was not possible to identify any significant differences between the mean pupillary diameters of each of the four FDT parts individually; therefore, pupillary diameter may not differentiate between controlled (parts three and four) and automatic processes (parts one and two) in the FDT. However, the difference appeared when comparing the first block of parts two and three (Retrieving and Inhibiting) and three and four (Inhibiting and Shifting), but not when comparing the second block. This may be because the participant had not yet developed an efficient strategy in the first blocks, which may come later in that same part. In other words, that part was not yet affected by learning and can be a purer measure of these processes. Despite using another "task (a visual search for a target), Takeuchi *et al.* [24] found similar results in their study: pupil size increased in early stages of the task, and decreased considerably at the end of that task, but never at a lower level than before testing, where there was no cognitive effort. It is possible that the first block can be more sensitive to the difficulties presented to an individual during the test. The absence of this pupillary size reduction may be a more sensitive indicator of one's experienced difficulty than time to complete the task. Porter *et al.* [25] analyzed tasks with variable degrees of difficulty and found that only the different pupillary diameter, and not time to complete the task, indicated that there was cognitive effort. As proposed by Sedó [20], this learning effect has to be further explored as it may enlighten subtle difficulties underlying the learning process, while pupillary data may provide real time information regarding it. It is important to consider that part four (Shifting) requires flexibility and attentional scanning, two cognitive functions regulated by the tonic state of the locus coeruleus [26]. From the studies in monkeys, it is known that the locus coeruleus is highly related to pupillary dilation (e.g. [27]). Thus, pupillary diameter may act as a measurable physiological variable that could indicate locus coeruleus' activity.

Table 1. Repeated samples t-test for block 1 (the first 25 stimuli) of the FDT. Sig.[b] provides the actual probability level. The significant differences are identified in boldface.

FDT Part		Mean difference	Std. error	Sig.[b]	95% Confidence interval for difference[b]	
					Lower bound	Upper bound
1	2	0.147	0.081	0.084	-0.022	0.316
	3	0.022	0.038	0.567	-0.057	0.100
	4	-0.071	0.039	0.088	-0.153	0.012
2	1	-0.147	0.081	0.084	-0.316	0.022
	3	-0.125	0.087	0.164	-0.306	0.056
	4	**-0.218**	0.089	0.023*	-0.403	-0.033
3	1	-0.022	0.038	0.567	-0.100	0.057
	2	0.125	0.087	0.164	-0.056	0.306
	4	**-0.093**	0.030	0.006*	-0.156	-0.029
4	1	0.071	0.039	0.088	-0.012	0.153
	2	**0.218**	0.089	0.023*	0.033	0.403
	3	**0.093**	0.030	0.006*	0.029	0.156

One important factor that cannot be accounted for in our results is the fatigue associated with the cognitive task. Young *et al*. [28], found that, while reading texts, pupillary diameter is reduced as an effect of fatigue. The fact that no significant differences between pupillary diameter of each part (from both control task and FDT) were found could mean that this task is not demanding and therefore does not cause fatigue. On that account, as a relatively short task with pauses between each part, it is plausible that the FDT may not have this disadvantage.

The results presented in this study further elaborate cognitive and learning aspects involved in the FDT. In comparison with control stages, it is possible to recognize that the growing difficulty of each of the tests' stages is reflected on the pupillary diameter, indicating sustained cognitive effort. The limitations of this study are related to the small sample analyzed and the fact that no other measurements of executive functions were carried out in order to control for factors which may affect FDT results, such as fluid intelligence. Future studies may also take in consideration eye tracker data such as fixation time during the execution of controlled and automatic processes.

Conclusions

The present study demonstrated that different pupillary diameters could distinguish controlled from automatic cognitive processes between the first and second half of the FDT. It also provides evidence that the subject's pupil size is greater at the beginning of the task. These findings can enlighten future studies that may investigate the role of cognitive effort in executive functions. It is important to perform comparative studies with imaging techniques like functional magnetic resonance imaging (fMRI), as the clinical applicability of the pupil diameter measurement is a promising physiological marker for cognitive effort. Moreover, it is necessary to evaluate this technique's application in a population with different mental ilnesses, particularly when there are difficulties in evaluating cognitive abilities via conventional assessment tools. As shown by Minassian *et al*. [11], patients with schizophrenia tend to display reduced pupillary dilation over complex stimuli when compared to controls, which could be a consequence of their attentional impairment and cognitive overload.

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Conflict of interest statement: The authors declare no conflict of interests.

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