COGNITIVE PROCESSES CAUSING PUPIL DILATION IN A SEQUENTIAL MULTITASKING EXPERIMENT

Bachelorproject

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Abstract: Changes in the size of the human eye pupil can be caused by various cognitive processes. Recent studies have revealed that the eye pupil dilates just before switching to a secondary task during a sequential multitasking experiment. One way to explain the pupil dilation is the planning involved in the decision to switch. In the experiment, participants were asked to play several games of Concentration, consisting of cards with linear equations to be solved. Participants had to switch to the secondary task for at least three times per game. In this study, a new condition was added in the form of a different secondary task, which was entirely optional. An increase in pupil size was found in both conditions in the moment before the switch. There was no significant difference between the conditions, which indicates that deliberate planning was not part of the decision process causing the pupil dilation.

1. Introduction

The size of the pupil varies depending on changes in the light intensity. If the light intensity is high, the pupil contracts to decrease the amount of light reaching the retina. Vice versa, if the light intensity is low, the pupil dilates to let in more light. Pupil size also depends on other factors, one being mental activity. This was first explained by the German neurologist Bumke in the beginning of the 20th century, who reasoned that every active mental process, every psychical effort, every active mental image and every affect produces an increase in pupil size (as cited in Beatty & Lucero-Wagoner, 2000). A few decades later, the dilation of the pupil became known as an indication for arousal or interest in a particular subject (Hess & Polt, 1960). In the 1980s, pupil dilation was established as a valid measure for cognitive effort (Beatty, 1982). An element of cognitive effort is memory load or processing load. It was found that the pupil size was closely related to the amount of memory load, as the pupil size increased with a higher memory load (Kahneman & Beatty, 1967).

More recently, Moresi et al. (2007) showed that pupil size can be a valid measure of cognitive load in the domain of response preparation. In a finger-cuing task, it was found that the amount of pupil dilation increased with more difficult response sets. The pupillary response is found to be slow, as it increases gradually and peaks after approximately one second following the event that caused the response (Wierda, van Rijn, Taatgen & Martens, 2012). However, an Attentional Blink experiment revealed that "the pupil dilation can be used as a marker of cognitive processing in the time scale of ~100 ms" (Zylberberg, Oliva & Sigman, 2012), which shows that pupil dilation reveals the timing as well as the amount of cognitive processing. The study by Wierda et al. (2012) originally started this approach by showing that the dynamics of attention and cognitive processes on a shorter time scale (at high temporal resolution) can be obtained from the slow response of the pupil using a technique called automated dilation deconvolution.

Other research, in the field of decision making, found that uncertainty in a decision involving rewards led to increased pupil size (Satterthwaite et al., 2007). The studies that are mentioned above led to the expansion of pupillary research to the domain of multitasking.

Preliminary results in ongoing research have shown that pupil dilation occurred just before switching to a secondary task in a sequential multitasking experiment (Taatgen & Katidioti, personal communication, March 2013). A possible explanation is the planning involved in the decision process to switch. As the current research is based on this ongoing research, the experiment and the results that are found so far will be explained in more detail.

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1.1. Sequential multitasking

Sequential multitasking is defined as switching between tasks "after lengthy periods of execution on only one of the tasks" (Salvucci & Taatgen, 2010), as opposed to concurrent multitasking, where multiple tasks progress simultaneously or with short interruptions. In the experiment that is part of ongoing research by Taatgen & Katidioti, the main task consists of solving equations in a game of Concentration. The secondary task is a short performance task called *n*-back. Both tasks will be fully explained in section 2.4 and 2.5.

This experiment is a typical example of sequential multitasking, because participants continuously spend time on the main task, solving equations and remembering positions of cards. There may be a slight moment of overlap, when they switch to the secondary task, as they could rehearse some information about the concentration game while preparing for the secondary task, but in general it is only possible to focus on one of the tasks at a time.

There are four different conditions for the secondary task in the experiment. The *n*-back task was either forced or voluntary, and both of these conditions had either a three-second delay or no delay. Forced means that the *n*-back task could interrupt the main task at any given time during the concentration game. In the voluntary condition, participants could choose when to switch to the secondary tasks themselves by right-clicking on a card, but they were told to switch at least three times in a game. In total, the experiment consisted of twelve games of concentration. To test all four conditions equally, each condition only appeared in three games, in random order. To summarize, the four different conditions are: forced with delay, forced with no delay, voluntary with delay, and voluntary with no delay.

It is interesting to note that the memory load in the study by Taatgen and Katidioti does not seem to be reflected in the pupil size so far, as opposed to what might be expected from earlier research (Beatty, 1982; Kahneman et al., 1967; Moresi et al., 2007). One possible explanation for this is that the memory load in this particular situation, remembering the outcome of equations and the position of cards, is spread out over a time frame that is too large. For example, the memory load only increases by 1 every ten seconds when a new card is opened and no match is found, which may be too long to find a significant change in pupil dilation.

The main observation in the experiment is the discovery that the pupil dilates just before switching to the secondary task, and that it peaks around the moment of the switch. There are various explanations possible for this phenomenon, which are discussed in more detail in section 4. The possible explanations are: switching from goals; rehearsal of the concentration game; preparing for the secondary task; the decision to switch; or planning the decision to switch. In the study by Taatgen and Katidioti, several attempts have been made to rule out some of these explanations, with the goal to narrow it down to one.

It was also found that there was no significant difference in the pupil dilation between the delay and no-delay condition just before the switch. For the current research, the delay and no-delay conditions are not used. Instead, the focus was put on the question whether deliberate planning is involved in the decision to switch. This question formed the beginning of the current research.

In this study, a modified version of the original experiment is used. Only one condition was kept the same, which is the voluntary condition with no delay. A new second condition was added, which did not require a minimum amount of switches to the secondary task.

1.2. Hypothesis

It will be interesting to see the differences between the two conditions. What is the role of the planning involved in the decision process that can be the cause of pupil dilation? It was already clear that the pupil dilation was very robust in the early results from Taatgen and Katidioti, as pilot results with a small sample size of 3 showed the same results as a previous experiment, indicating that the effect is rather stable. This has consequences for this research, because comparing differences between the two conditions can be easier when the variation within a condition is low.

It is expected that both conditions will show an increase in pupil size just before switching to the secondary task.

2. Methods

2.1. Participants

Twenty-one students from the University of Groningen participated in the experiment (6 female; average age 20.6 years; range 17-26). The subjects received a monetary reward for their participation. Informed consent was obtained from each participant before testing.

2.2. Task design

The experiment consists of a main component, the concentration game, which is the same for both versions of the experiment. The secondary task is different for each version. The design of the experiment is between subjects, therefore participants were randomly divided into two groups. Ten participants did the n-back version of the experiment, and eleven participants did the music version.

The experiment has a total of twelve concentration 'games' or blocks. All cards were 'shuffled' in each block. A separate practice experiment consisting of two easier blocks was conducted to explain the concentration game and the secondary task.

To prevent fatigue and to keep the experiment duration reasonable, considering the monetary reward and the cognitive load on the subjects, a time limit was introduced and set at 45 minutes. When this limit was reached, no more blocks were started after the current block was finished. If participants were slow in the concentration game, it could happen that the experiment stopped after block 9 or 10 because the time limit was reached.

2.3. Setup and apparatus

The room where the experiment was conducted had no windows, and was lit by two fluorescent tubes at the ceiling. Participants were tested one at a time. The setup was composed of a standard keyboard and mouse, and a Dell 20" Flat Panel Monitor with a resolution of 1600×1200 pixels. The experiment screens were produced by Mathworks Matlab 2010, using Psychophysics Toolbox Version 3 (psychtoolbox.org), running on a MacBook Pro. An EyeLink 1000 eye tracker (www.sr-research.com) was used to measure the pupil size during the experiment. A chin rest with forehead support was used to ensure a stable measure. The gaze and pupil size of the left eye were measured at 250 Hz. The eye tracker camera was placed below the computer screen at about 50 cm from the chinrest. Participants were able to adjust the chair and the chinrest to find a comfortable position for the experiment. For the secondary task that involved music playback, the volume was set at a medium level.

2.4. Concentration game

The main component of the experiment, the concentration game, will be explained first. In a traditional game of concentration (also called Memory or Pairs), one has to find two cards with the same picture (a pair). When turning the cards back, because no match was found, one has to remember the position of each card, along with the picture of that particular card.

The concentration game in this experiment is more difficult. It consists of a 4 by 4 grid representing cards. On the back of each card is a linear equation in the form $\mathrm{A} * \mathrm{X} + \mathrm{B} = \mathrm{C}$. Two cards form a pair when they have the same value for X. For example, a card with the equation $5 * \mathrm{X} + 5 = 30$ can be matched with the card containing the equation $3 * \mathrm{X} + 4 = 19$. Solving both equations gives $\mathrm{X} = 5$, therefore these cards form a pair. Instead of keeping track of cards and pictures, like in a normal concentration game, subjects had to remember the solution to a particular equation along with the position of the card that contains the equation.

Cards can be opened by clicking them with the left mouse button. Only one card can be shown at a time. If another card is clicked, the previous-clicked card flips back. In a normal concentration game, one would turn two cards in succession, then compare them and flip them back together if they are different. Because equations are more difficult, participants are restricted to flip only one card at a time. When two matching cards were clicked after each other, they would both flip and permanently show the text 'MATCHED!' for the rest of that game. See Figure 2.1 for an example.

When all cards in a game are matched, that specific game ends, and a blank screen with a text message appears, telling the participant that it is possible to take a small break, before starting the next block with a key press.

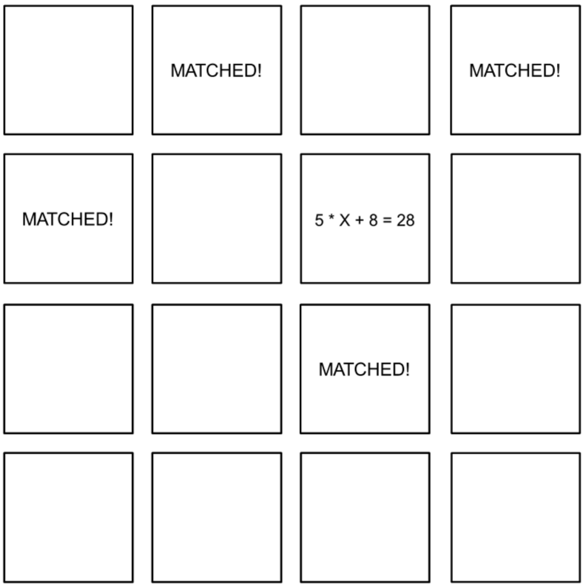

Figure 2.1: The concentration game, consisting of sixteen cards in a 4 by 4 grid. Two pairs of cards are already matched in this example. The open card shows the linear equation 5 * X + 8 = 28. Solving this equation gives the solution X = 4. Another card with the solution X = 4 has to be found to match this particular card.

To start the secondary task, subjects have to right-click on a card. Starting the secondary task on an already matched card is not possible. If a new block just started, or if the secondary task just finished, it is impossible to start the secondary task (again), without opening at least 2 cards. Switching to the secondary task is allowed for a maximum of 6 times per game. Attempting to start the task after the limit has been reached results in the message 'Denied' appearing in the clicked box for a short moment.

The concentration game is located in the center of the screen. At the top of the screen, a text message is displayed, depending on the condition of the experiment. For the *n*-back condition, this message reads "Press right mouse button to start *n*-back". For the music quiz condition, the word *n*-back is replaced by "music quiz". The message is extended by a brief score display, consisting of the text "Total score:" followed by a colored percentage indicating the relative amount of correct answers. The color is green if the score is 75% or higher, yellow if the score is in between 75% and 55%, orange if it is in between 55% and 35%, and red if the score is below 35%.

2.5. *n*-back

The secondary task in the first condition is similar to the voluntary condition used before in the research by Taatgen and Katidioti. The secondary task is a performance task called the *n*-back task, which was originally developed by Kirchner (1958). This task "requires judging whether a new item is identical to the *n*th-item back in a sequentially presented list of items" (as cited in Juvina & Taatgen, 2007).

For both the original experiment and the current study, 2-back is used. When the *n*-back task is initiated by a right-click on a non-matched card, the text 'NBack' appears for a brief 0.5 seconds. One second later, a sequence of letters is presented to the subject at a rate of one letter in 2-2.5 seconds, depending on the answer speed of the subject. The first two letters require no input. Beginning at the third letter, participants can press either the 'z' key to indicate that the current letter is the same as two letters back in sequence, or they can press the 'x' key to indicate that the current letter is not the same as two letters back. After a button has been pressed, a green or red circle appears around the letter, indicating a correct or incorrect answer respectively. If no answer is given after 1 second, the answer is regarded as incorrect and a red circle is shown.

The total duration of the task is 21 seconds and the probability of a stimulus being the same as 2 letters back in sequence is 50%. The stimuli consist of the following letters: C, H, I, K, L, Q, R, S, T and W. If the time limit of 21 seconds is reached, no more stimuli are shown and the task is ended. If the *n*-back started on an open card, the card is opened again after finishing *n*-back.

2.6. Music quiz

A new secondary task has been developed for the second condition. Essentially, this task is a short music quiz, in which the participant should guess the song title or artist of the music fragment that is playing. The music fragments are selected from popular music charts, for example from the Dutch Radio 2 Top 2000 (www.top2000.nl), and Radio 538's Top 40 (www.top40.nl).

When participants switch to the music quiz by right-clicking on a (non-matched) card, they are informed that the music quiz will start in the same way as the *n*-back task, but with the text 'Music Quiz'. After that, music will start playing, but the screen will not show the answers until two seconds have passed. This is to prevent causing pupil dilation too close to the moment of the switch by sudden change of the screen. After two seconds, the concentration game disappears, and a blank screen with four answers is shown, comprised of either artists or song titles.

Each song fragment will play for exactly 8 seconds. As soon as the answers are displayed on the screen, subjects can choose their answer with the numbers 1, 2, 3 and 4. The numeric keypad does not register answers. Once an answer has been chosen, feedback in the form of a green or red circle will appear. When subjects guessed the right answer, a green circle will appear around the number of that specific answer. If they guessed the wrong answer, a red circle appeared around their answer, and an additional green circle appeared at the right answer. When the playback has stopped, subjects have an additional 2 seconds to select an answer. If no answer is given, the correct answer is shown by displaying an orange circle.

The music quiz consists of two fragments in total, and the second fragment starts playing two seconds after the first fragment finished playing. After the second fragment is finished, the concentration game is drawn back on the screen, including already matched cards (if any). If the subject started the music quiz on an opened card, that particular card is opened again. The score is updated at the top of the screen, where the percentage of the right answers is shown.

2.7. Procedure

The experiment started with participants signing the informed consent form. It was explained that they were going to play a slightly different version of a game of concentration, while their pupil size was being measured. The chinrest and forehead support were adjusted for each participant. To make sure every participant fully understood the experiment, they had to do a practice run to become familiar with the concentration game and the secondary task. For this practice run, a modified version of the experiment was used, consisting of only two blocks. It was possible to skip each block at any given time by clicking on a big rectangle in the top center of the screen. In the first block, equations were replaced by integers (1-9). The goal of the concentration game was explained by the instructors, while participants could try to match cards by left-clicking them.

The secondary task was explained, by telling the participants to right-click on a card and explaining in detail what was happening next and what buttons the participant had to press. For the *n*-back condition, participants were told to switch to the *n*-back task at least three times per block. If they did not switch at least three times, a message was displayed after completion of the block to inform them that they should to the task at least three times in the next blocks. For the music quiz condition, participants were told that they could switch to the music task anytime they want, but that it was not mandatory.

The second and final block of the practice experiment consists of easier equations, e.g. $2 + X = 8$. In these equations, only the mathematical abilities 'add' and 'subtract' are used to solve the equation, eliminating the need to multiply and divide. When the participant understood the experiment, the practice run was terminated by the instructor.

The eye tracker was calibrated using the calibration setup from the EyeLink software, by showing targets at different locations on the screen to focus on. These targets were validated in the next step. After calibration, the experiment starts with some questions about the age and sex of the participant. Next, the first block is shown, after a drift check was done. Participants were able to take a short break in between each game of concentration. Prior to starting a new block, a drift correction was performed, as participants could have moved their head during the small breaks. The experiment was terminated when all twelve blocks had been completed, or when the current block had been completed and the time limit of 45 minutes was reached. In the music quiz condition, the total score percentage was shown to the participants after completion of the last game.

2.8. Pupillometry and data preprocessing

The pupil size is recorded at 250 Hz. To prepare the raw data for analysis, it was preprocessed in different steps. First, the data files generated by the eye tracker were converted to the .ASC file format, which is a normal text file format. Next, a Python script processed each file line by line and created files in a table-like format that can be used as input for the statistical package R (http://www.r-project.org, version 2.15.3).

In R, a script was executed that removed artifacts such as eye blinks. It also down-sampled all data to 100 Hz. The removal of artifacts was done by removing any measurements with an absolute dilation below 500, which is considered as a blink. Sudden downward jumps were removed as well. A margin of 100 ms was also removed around each artifact. The removed data was replaced by linear interpolation.

To be able to compare the pupil dilation between participants, the absolute pupil dilation was converted to a relative dilation in a percentage change compared with a baseline. This baseline was created by using a very slow lowess on all the data.

2.9. Analysis

For the analysis of the pupil dilation around the moment of switching to the secondary task, a window was used from 5 seconds before the switch to 10 seconds after the switch, aggregating all switch moments from every participant per condition. T-tests were performed for every sample (10 ms) to indicate significant differences between the two conditions. Performance was measured based on the number of revisits. A revisit is the event in which a card has been seen before and is clicked (opened) again. Less revisits means that participants performed better in remembering the position and solution of the cards. To analyze the performance and the presence of a possible learning-effect, linear mixed effect models were used on all the data. This analysis was done by using the lmer-function from the lme4-package in R (www.r-project.com, version 2.15.3).

3. Results

Figure 3.1 shows the average pupil dilation for both conditions over all participants. It is clearly visible that the pupil size increases just before the switch to the secondary task. The dark grey areas in the background show the moment in time where the difference between the two conditions is significant ($p < 0.05$). Relevant to this research is the five-second time frame prior to the switch, which contains only one small interval of about 100 ms where the difference

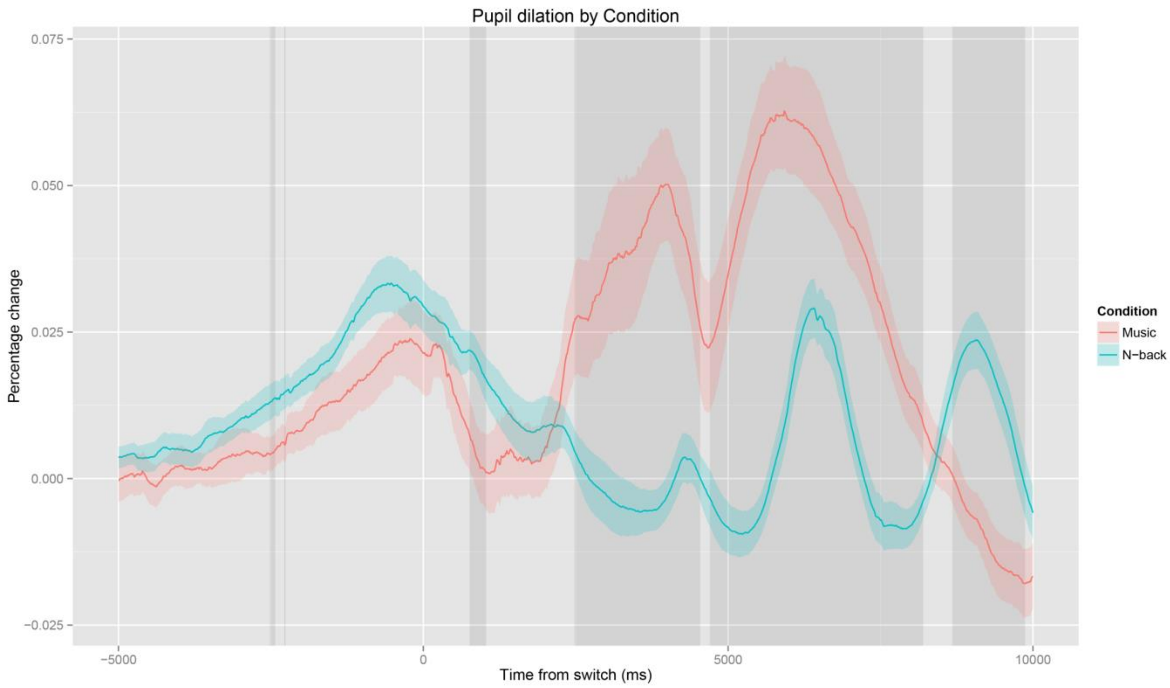

Figure 3.1: Average pupil dilation by condition over all participants. The green graph is the *n*-back condition, the red graph is the music quiz condition. Colored areas around the graphs indicate the standard error. Dark grey areas in the background indicate a significant difference between the two conditions ($p < 0.05$). The time frame ranges from 5 seconds before the switch to 10 seconds after the switch.

was significant. In the rest of the interval, the difference was not significant.

The graph of the music quiz condition is consistently lower before the switch, but the difference with the *n*-back graph is not significant. The much higher peaks after the switch are probably caused by the difference in the tasks. In the *n*-back graph, the moment of the first and second stimulus appearing is clearly visible at about 6.5 seconds and 9 seconds after the switch. For the music quiz condition, the high peaks are possibly caused by the music that started playing, which apparently caused a very different effect on the pupil dilation.

A significant practice effect was absent when comparing the performance in the first six blocks with performance in the last six blocks; subjects did not perform better on the concentration games later in the experiment. However, an effect of the number of switches per block on the performance was found in the music quiz condition only ($\beta = 4.64$, SE = 1.50, $p < 0.05$). See Figure 3.2. More switches resulted in more revisits, indicating that subjects performed worse when they switched to the music quiz more frequently.

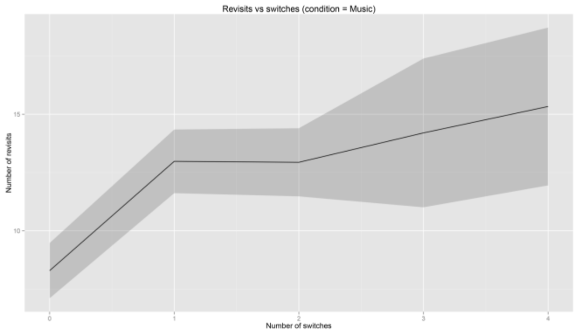

Figure 3.2: Effect of the number of switches on the number of revisits (the performance). The dark grey area around the graph is the standard error.

4. Discussion

The goal of this study was to investigate the role of the pupil dilation in a sequential multitasking experiment, and more specific, to determine whether deliberate planning was involved in the decision process that caused the pupil dilation. Based on results found in prior research, it was hypothesized that there would be an increase in pupil size in both conditions just before the switch to the secondary task. The results confirmed this hypothesis, and a significant difference between the *n*-back condition and the music quiz condition just before the moment of the switch was not found, as seen in Figure 3.1.

There are multiple explanations possible to interpret this result. These explanations will be discussed with the ongoing research (Taatgen & Katidioti) in mind. First, the pupil dilation can be caused by the cognitive process of switching goals. The goal in the concentration game is to match all the cards. When the switch to the secondary task takes place, this goal changes to a different one. For *n*-back, the goal is to correctly determine if the current letter was seen exactly two steps back in the sequence. For the music quiz, the goal is to correctly identify the music fragment that is being played. Further progress in the ongoing research by Taatgen and Katidioti is needed to draw conclusions about the likeliness of this explanation.

A second interpretation is that the pupil dilation is caused by rehearsing information in the working memory, resulting in a cognitive effort that is being reflected in the pupil size. This explanation would be expected according to earlier research (Beatty, 1982; Kahneman et al., 1967; Moresi et al., 2007). However, in the ongoing research by Taatgen and Katidioti, indirect evidence was found against this, as there was no difference found in performance between the voluntary conditions and the forced conditions in the original experiment. In the forced condition, participants would have no time to rehearse prior to starting the *n*-back task.

Another explanation that is slightly different from the second one, is the preparation for the task itself. This can be seen as a mental preparation where participants realize that they are going to do something else, and that they anticipate on what is coming next at the start of the secondary task. This was tested in the original experiment, by comparing the delay and no delay conditions. It was found that the peak for the first stimuli was only shifted backwards as a result of the introduced delay, but no significant difference was found in the moment before the switch.

Perhaps the most interesting explanation is that the pupil dilation is caused by the decision process to switch. The decision process can be divided in two separate explanations, one being a faster bottom-up process that is mainly driven by sensory information. The other process involves deliberate planning and is more of a top-down approach. The aim of the current research was to assess whether this distinction was reflected in the pupillary response. The results suggest that the deliberate planning component is not part of the cognitive process that caused the pupil dilation, because participants were able to choose whether they would switch to the music quiz. For *n*-back, participants had to reason about the larger picture of 'planning' at least three switches per block.

A last and yet simple explanation for the pupil dilation that cannot be ruled out so far, is that the event of simply clicking on the mouse caused the pupil to dilate. This seems unlikely, because the pupil size already increases moments before the switch. This explanation will probably be ruled out in the ongoing research by modifying the forced condition.

To summarize, the research by Taatgen and Katidioti has been attempting to rule out each different explanation. At this point, the results so far suggest that it comes down to the cognitive process of the decision to switch, not involving deliberate planning. More research is definitely needed to draw conclusions, which will only be the tip of the iceberg; to explain the cognitive processes is another endeavor.

The current research hopefully contributes a useful piece of information to the puzzle of pupil dilation in a sequential multitasking experiment. Along with the recent discovery that the pupil constricts as a response to a picture of the sun (Binda, Pereverzeva & Murray, 2013), the research of Taatgen and Katidioti will, in time, help to reveal more of the underlying cognitive processes that cause the human eye pupil to dilate or contract.

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