Cognitive processes causing pupil dilation in a sequential multitasking experiment

(Bachelorproject)

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Abstract

Certain cognitive processes are reflected in dilation of the human eye pupil. In ongoing research, it was found that the eye pupil dilated just before participants made a decision to switch between tasks during a sequential multitasking experiment. There are several possible explanations for this phenomenon. Two of these explanations involve making a decision. The pupil size increase could be caused by a 'pure' decision, or by a decision which involves deliberate planning. The current research is an attempt to rule out the planning factor by introducing a condition which is entirely voluntary. The involuntary condition - the subjects were told to switch to the secondary task a fixed number of times - remained. Both conditions showed a sudden increase in pupil size just before the participants pressed a button to switch to the secondary task. No significant difference between the conditions was found, indicating that the increase in pupil size was mainly caused by a decision process which did not involve a deliberate planning component.

1 Introduction

It is well known that certain cognitive processes are reflected in dilation of the human pupil. Bumke (1877 - 1950), a German neurologist, already found that anxiety produces a dilation of the human pupil (as reviewed by Gang (1945)). Moreover, he stated that 'every active intellectual process, every psychical effort, every exertion of attention, every active mental image, regardless of content, particularly every affect just as truly produces pupil enlargement as does every sensory stimulus' (as translated in Hess (1975)).

The study of pupil dilation particularly became popular in the 1960s and 1970s. During those decennia, pupil dilation proved to be a reliable measure for cognitive processes. In a review about the task-evoked pupillary response, Beatty concluded that the pupillary response is a valid measure of processing load or 'mental effort' required to perform a cognitive task (Beatty, 1982). More detailed, it was found that a higher memory load triggered dilation of the pupil (Kahneman and Beatty, 1966; Van Gerven, Paas, Van Merriënboer, and Schmidt, 2004; Karatekin, 2004). Memory strength is reflected in dilation of the pupil as well. Researchers found that the easier an item could be retrieved from memory, the less the pupil dilated (van Rijn, Dalenberg, Borst, and Sprenger, 2012).

In recent years, pupil dilation has been linked to certain decision processes. In an experiment by Satterthwaite, eye pupil size was monitored during a gambling task involving decision making (Satterthwaite, Green, Myerson, Parker, Ramaratnam, and Buckner, 2007). In Satterthwaite's experiment, two regular playing cards were shown to participants. One of those cards was displayed face-up, the other face down. Subjects had to predict which of both cards would turn out to carry the highest number when the face-down card was turned over. Three levels of reward uncertainty were distinguished by taking the value of the face-up card into account: uncertain (face-up card was 6, 7, 8, 9 or 10), probable (cards 3, 4, 5, J, Q, K) and certain (cards 2, A).

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The experimenters found that a higher uncertainty was reflected in a higher pupil diameter size. This process of eye pupil dilation began even before the face-down card was turned. They also found that the eye dilated more during a feedback epoch when a loss was unexpected (i.e. when a wrong decision was made when the uncertainty level was probable).

1.1 Pupil dilation in multitasking

In 'The Multitasking Mind' - a book by Salvucci and Taatgen on multitasking from a cognitive point of view - a theory named *threaded cognition* is introduced (Salvucci and Taatgen, 2010). In that theory, a distinction is made between concurrent multitasking and sequential multiasking. Concurrent multitasking describes the phenomenon of multiple tasks which have to be performed simultaneously, whereas sequential multitasking is about performing two tasks sequential: one after another.

Ongoing, unpublished research by Taatgen and Katidioti has attempted to link eye pupil dilation to specific multitasking processes. They found an increase in pupil dilation during a sequential multitasking experiment at the time of switching between two different tasks. A game inspired by the classic board game concentration acted as the primary task in the experiment, while another working memory intensive task called n-back (Kirchner, 1958) fulfilled the role of secondary task. Pupil dilation peaked just before participants pressed the right mouse button to switch to n-back. This indicates that the increase in pupil dilation was caused by a process in the mind which prepares for a change in tasks. In the experiment, a condition with a delay between the decision and the beginning of the task did still show the same peak in pupil dilation. The delay did not have an effect on the temporal location of the increase in pupil size.

There are roughly five explanations for the dilation of the pupil during sequential multitasking, which will be discussed in more detail in the discussion section of this paper:

(1) Change of goal;

(2) Rehearsal of items in concentration game;

(3) Preparation for the secondary task (n-back);

(4) The decision to switch;

(5) The pressing of the right mouse button.

The decision to switch (4) can be split into two parts: a possible planning component and the decision itself. When the first component is absent, one could call such a decision a *pure decision*. In the other case, when the planning component is really part of the decision, one could speak of a *decision involving planning*.

A characteristic of the second task in Katidioti's and Taatgen's experiment was that n-back was never entirely voluntary. Participants had to finish 12 blocks of memory, and were asked to do at least three switches to n-back. As a consequence, the peak in pupil dilation near the moment of switch could as well be triggered by the involuntariness of the experiment. The rememberance of the fact that the participant still had to switch another time, for example, could have caused an increase in pupil dilation. In other words: the planning component previously mentioned could have had an effect on the increase in pupil size.

Therefore further research is necessary to unravel the origin of the cognitive processes which caused the pupil size increase. In the current research, an experiment with both a voluntary and involuntary condition is performed. The involuntary condition featured the same memory game and secondary n-back task as used in Taatgen's and Katidioti's experiment. Participants were told to switch at least three times to n-back. The voluntary condition consisted of the memory game alternated by a music quiz which fulfilled the role of secondary task. In this condition participants were free to switch as many times as they would want to. In this way the music/voluntary condition did not feature a possible influence of a planning component which is part of the decision.

The current research is an attempt to rule out factors which could possibly influence the eye pupil size during sequential multitasking. With both a voluntary and involuntary condition, a possible difference between the two conditions in eye pupil dilation could be explained by the (in)voluntariness of the conditions. The hypothesis, however, does not account for involuntariness as a factor of influence. The expectation is that both conditions show the same peak in pupil dilation just before switching, caused by a decision process which is not affected by deliberate planning.

2 Methods

2.1 Participants

The participants were students of Rijksuniversiteit Groningen (Groningen, The Netherlands). A total of 21 subjects (5 female) performed in the experiment. They aged between 17 and 26 years.

2.2 Materials

There were three tasks which functioned as the building blocks for the experiment:

Concentration game Subjects played a game which was based on the classic board game concentration. They, however, did not match pictures. They solved equations instead and then matched values for a variable x. The cards containing equations $3 * x + 5 = 20$ and $7 * x + 4 = 39$, for example, match, as the variable x holds the same value of 5. The equations were of the form $a * x + b = c$. a and b ranged from 2 to 9. x was the variable which had to be solved and ranged from 2 to 8.

The concentration game consisted of a grid of 4 by 4 (16 cards) on a white background (figure 1). The cards were displayed in a very minimalistic way by white rectangles with a black border drawn around them. Every card throughout the entire experiment contained a unique equation. The participants could flip the cards by clicking them with the left mouse button. The content of a maximum of one card was visible at a time. When a card was flipped and no match was constructed, the previously shown card was being flipped back. To match a pair of cards, the particular cards had to be clicked one after the other. A label 'MATCHED' was attached to these cards. When all cards were matched, a concentration block was finished.

Music fragment quiz The music fragment quiz consisted of two fragments of pop songs (duration of a single fragment: 8 seconds) which were played one after another. While a fragment was playing, four answers consisting of either song titles or song artists were displayed on the screen. Subjects had to pick one answer out of these four. The answers were displayed in the middle of the screen. Subjects could answer by pressing 1, 2, 3 or 4 on the keyboard with their left hand. Numeric pad key presses were not registered. The type of answer - song title or artist - differed because otherwise some of the songs would be too easy or too hard to guess. Feedback was given by drawing a green circle around the right answer and, if participants guessed wrong, a red circle about the wrong answer. When answering took too long, the correct answer was marked with a yellow circle. The music task terminated automatically after playback of two songs (total duration: 16-20 seconds; subjects had some additional time to answer after playback had finished).

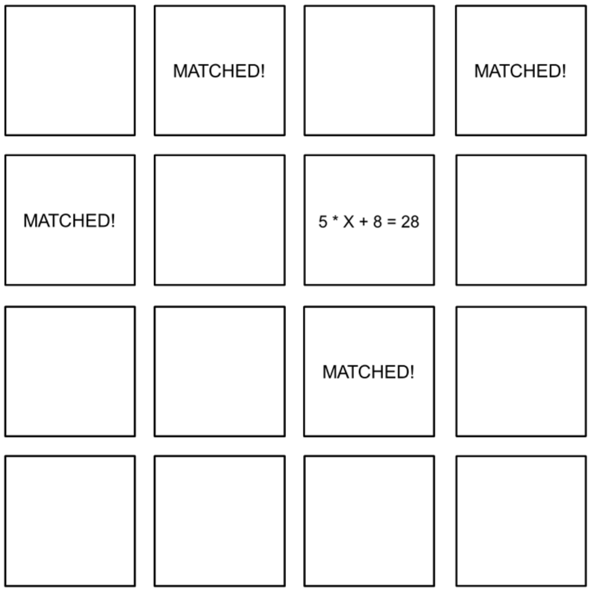

Figure 1: The concentration game

The fragments were extracted from popular songs which were either very recent or older but very well-known. The fragments mainly consisted of (a part of) the chorus of the popular songs, as this is a recognizable part. The audio editor Audacity was used to export the fragments to a file format readable by MATLAB.

2-back 2-back, or n-back in its more general form, is a task which shows a sequence of consonants. After the first two letters were shown, the subject had to decide whether the current letter was the same as the one showed two letters before. The participant answered with either the 'z' key (to confirm that the letter was the same as two rounds before) or the 'x' key (to deny). Feedback was given on both correct and incorrect answers: a green or red circle was drawn around the n-back letter which was displayed at that exact moment. Subjects could give their answer as soon as a letter appeared.

2.3 Procedure

The experiment consisted of two conditions: n-back and music. Each participant only did one of the two conditions: a between-subjects design. The design of the experiment is as follows:

(1) Concentration game, alternated with a music fragment quiz as a secondary task;

(2) Concentration game, alternated with 2-back as a secondary task.

The concentration game can be considered the main task of the experiment. Participants either had to solve a total of 12 blocks or reach a time limit of roughly 45 minutes* to let the experiment terminate. During the concentration task, participants were able to switch to the secondary task by clicking a card with the right mouse button. There were some restrictions: when a concentration block had just started, participants could not switch to the secondary task; they had to turn two cards first. The same applied when the secondary task had just ended. These restrictions were set because otherwise there would not be a switch between different tasks at the described events. When partipants right clicked a box, or card, the name of the secondary task ('Music Quiz' or 'N-Back') was printed on the card. Then, after a one-second delay, the secondary task began.

There was an environmental difference between condition (1) and condition (2). In condition (1), the concentration grid disappeared after a two second delay to make space for drawing of the answers. As a consequence, playback of the first music fragment had already started when no answers were visible yet. The delay of two seconds was necessary because a change in environment can trigger a change in pupil size. Now it was guaranteed that the pupil size around the moment of interest - the switch - was not affected by any visual changes. There were no visual changes after the switch in condition (2). Because n-back is visually very compact, it was possible to display the task in just one concentration box - the one which was clicked to initiate the switch to the secondary task.

There was a major difference between condition (1) and condition (2). In condition (1), the music fragment quiz was completely voluntary. Whenever the participants felt like it, they could switch to the secondary task. If no switches were made, the participant was not punished. N-back in condition (2), in contrast, was not voluntary, at least not in this way. The *times* of switching to the secondary task were still voluntary, but the participants had to do at least three n-back tasks per concentration block. When the participants did not match this criterion, a warning message was displayed after finishing that particular concentration block.

Before the experiment started, participants were presented a trial task which made them familiar with the experiment. This trial task consisted of two concentration blocks. Subjects were free to skip these blocks whenever they felt they understood the concentration task and the particular secondary task. The experimenters supervised during the trial task, to make sure the participants fully understood. Especially the n-back task needed some explanation.

While the trial task explained most of the significant details, some additional information was given. In the n-back condition, participants were told to switch at least three times to n-back per concentration block. In the music condition, participants were told that they could do as many quizzes as they would like to do (although there was a theoretical cap of 6 music fragment quizzes per concentration block). Subjects were also informed about the switching restrictions previously mentioned: no switch possible when a concentration block had just started and when a secondary task had just been finished.

*The time check was made after finishing a concentration block. If experiment time exceeded the 45 minute limit, the experiment was terminated.

2.4 Data collection and post-processing

An eyetracker registered coördinates (x and y) and pupil size for the left eye every 0.004 seconds, which is 250 times per second. Additional details, such as memory load and times of switches from or to the secondary task, were also being stored. Finally, the program logged whether a click on a concentration box was a new visit, a revisit or a matching click. With this information it was possible to measure performance in the concentration game, which could be useful to detect a potential learning effect.

The acquired data was, for practical reasons, downsampled from a frequency of 250 Hz to a frequency of 100 Hz. Thereafter, an attempt was made to restore gaps in the eyetracker data by interpolating the data between the last known data point before the gap and the first data point after this gap. Gaps could have emerged because, for example, a participant looked away from the screen or simply blinked. The interpolation process was completely linear.

2.5 Analysis

2.5.1 Pupil size change

For every participant, a very slow lowess was used to approximate the acquired pupil size during the experiment. Because of its slowness, the lowess function did approximate pupil size well on a long time scale, but did not include rapid changes due to, for example, switching between tasks. Therefore, the lowess could be used as a baseline and made it possible to compare and merge results from different participants. For the relevant samples around the switches a percentage change of pupil dilation, relative to the baseline, was calculated.

The main research question was whether the voluntary music condition also shows a peak in pupil size just before switching. If so, how does this peak compare to the increase in pupil size for the n-back condition? An average graph was constructed to answer these questions. This graph showed a conditional pupil size change average over an interval of 15 seconds around the switch for every switch from primary to secondary task in the experiment.

The graphs for both conditions were compared by performing t-tests for every sample (sample size: 10ms). The pupil size for participants for a certain 10 ms interval was passed to the t-test. Thus the populations for every t-test in the experiment were of size 11 (condition: music) and 10 (condition: n-back). The intervals at which the t-tests yielded a significant p-value were marked in the already constructed graph.

2.5.2 Performance

It is important to measure all variables which could possibly have an effect on the dependent variable: eye pupil dilation. In the current experiment, it is possible that a learning effect can influence the pupil size in some way. An easier task could yield less pupil dilation when switching, for example. With a mixed-effects regression model an attempt was made to extract all parameters which had an effect on a certain performance measure, which is the amount of revisits for a concentration block. The number of revisits is a reliable measure of performance because it directly reflects the amount of mistakes made within a concentration block. A revisit occured when an already opened card was opened another time without matching this card directly. After aggregating data for every *block* of concentration, the following parameters were passed to the mixed-effects regression model:

(1) The number of switches to the secondary task that occured during a concentration block (independent variable);

(2) The block number (independent variable);

(3) The condition: concentration + music or concentration + n-back (independent variable);

(4) The total number of revisits for a concentration block (dependent variable).

2.6 Apparatus, setup

An EyeLink 1000 eye tracker was used to measure pupil coördinates and size during the experiment runs. Participants were tested in a windowless room with a constant illumination level. They sat on a chair behind a desk to which a chinrest was attached. The distance from the chinrest to the monitor was around 50 centimeters.

The experiment was programmed in MathWorks' MATLAB 2010a, which ran on a notebook with

Mac OS X. The Psychophysics Toolbox 3 (Psychtoolbox 3) extension for MATLAB was used for communication between MATLAB and the eye tracker device.

3 Results

Figure 2 shows the result for both the music and n-back condition. A dark gray background indicates a significant difference for the eye pupil size percentage change between conditions at a specific time.

At first glance both conditions show an increase in pupil dilation just before the switch. Keep in mind that there is a known delay of around 1 second before a cognitive process is reflected in the eye pupil diameter. The 'real' decision was probable made - if the change in pupil size in this experiment really reflects a decision process - around one second earlier.

There is a certain overlap in eye pupil dilation between the two conditions. Until around three seconds after the switch, little difference is shown. Both graphs climb to approximately an increase of around 2.5 percent. Further on, the lines each go their own way. This is as expected, because the secondary tasks, which had already started at that moment, are completely different.

3.1 Performance

A mixed-effects regression model (table 1 and table 2) showed a positive interaction between the condition (music/n-back) and the number of switches on the number of revisits per concentration block ($p < 0.05$). One could wonder whether only the interaction between condition and switches has an effect and not just the number of switches. This is the case because switches can not be used as a predictor for the number of revisits in the n-back condition. In that condition, people mostly switched three times to the secondary task per concentration block. Due to its more or less static value, the number of switches can not predict the number of revisits in the n-back case. We can conclude that the number of switches can be used to predict performance in the music condition: the more switches are made, the worse a participant performs in the concentration task. Another mixed-effects regression model which only considered the music data confirmed this ($p < 0.05$). Figure 3 shows a visualization of this effect for the music condition.

No effect of the block number on performance was found, which suggests that learning effects were absent.

4 Discussion

The results suggest that a deliberate planning component is not one of the main causes of pupil dilation at the moment of making a decision to switch between tasks. This confirms our hypothesis. At the interval that matters (from approx. three seconds before the switch to one second after), no significant difference between the voluntary condition and involuntary condition was present. Therefore, it is likely that a significant part of the pupil size increase can be assigned to a pure decision.

Recall that there are many other factors that could have caused the pupil size increase, as mentioned in the introduction section. Out of five factors, only one was examined in the current research. The other four factors that could possibly influence pupil size while making a decision to switch, however, do not seem very likely. These factors will be discussed in more detail in the following sections.

4.1 Change of goal

The pure change of goal - as being a cognitive process - could have caused dilation of the pupil. The results of an experiment by Taatgen and Katidioti do suggest that this was not the main reason of the pupil size increase.

That experiment did have four conditions which were tested within-subjects: forced + delay, forced + no delay, voluntary + delay and voluntary + no delay. Forced meant that the switch to the secondary task was not a decision by the participant but the program itself. Voluntary differed from the voluntary condition in the current experiment because subjects were told to switch to n-back at least three times per concentration block. In delayed conditions the secondary task did not directly start after announcement of the task, but after a short 1-3 second delay.

One would expect that when the change of goal was the main cause of pupil dilation, an increase in pupil size would be visible in all conditions: every

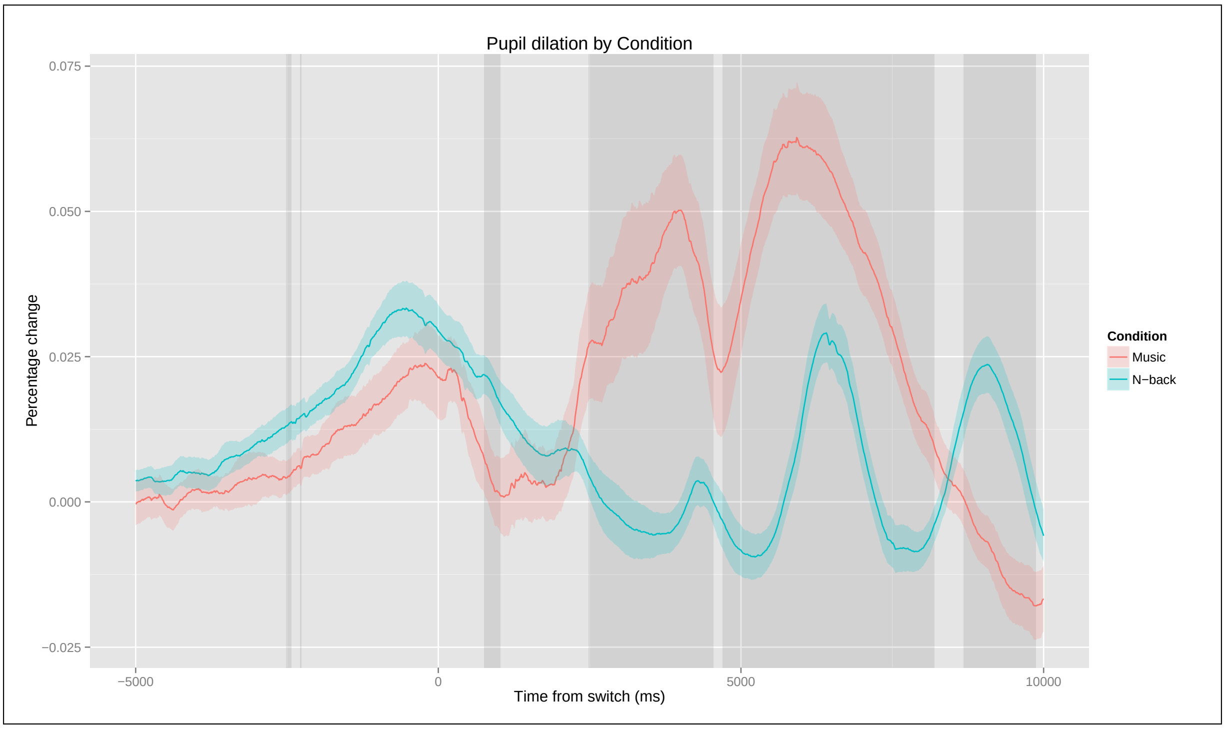

Figure 2: Average pupil dilation percentage change plotted against time for both conditions. At intervals with a dark gray background, the difference between conditions is significant.

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Groups	Variance	Std. Dev.
Participant	23.465	4.8441
Residual	52.330	7.2339

Table 1: Random effects of the mixed-effects regression model

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	Estimate	Std. Error.	t value	p value
Intercept	13.94895	5.46724	2.551	0.0114
Switches	-0.22263	1.64060	-0.136	0.8922
Block	-0.54419	0.95647	-0.569	0.5700
Condition1	-5.91403	6.02530	-0.982	0.3274
Switches:Block	0.03121	0.31486	0.099	0.9211
Switches:Condition1	4.85949	2.17463	2.235	0.0264
Block:Condition1	0.65383	1.01534	0.644	0.5203
Switches:Block:Condition1	-0.36046	0.36834	-0.979	0.3289

Table 2: Fixed effects of the mixed-effects regression model. Condition1 is the music condition.

condition involved a change from the concentration task to n-back. This was not the case. In forced conditions the increase in pupil size was much smaller than in the voluntary conditions, when the participants could make their own decision to switch.

4.2 Rehearsal

Another possible cognitive process which could influence the pupil size at the moment of switch is rehearsal of concentration card variables. Participants reported that it was hard to remember the

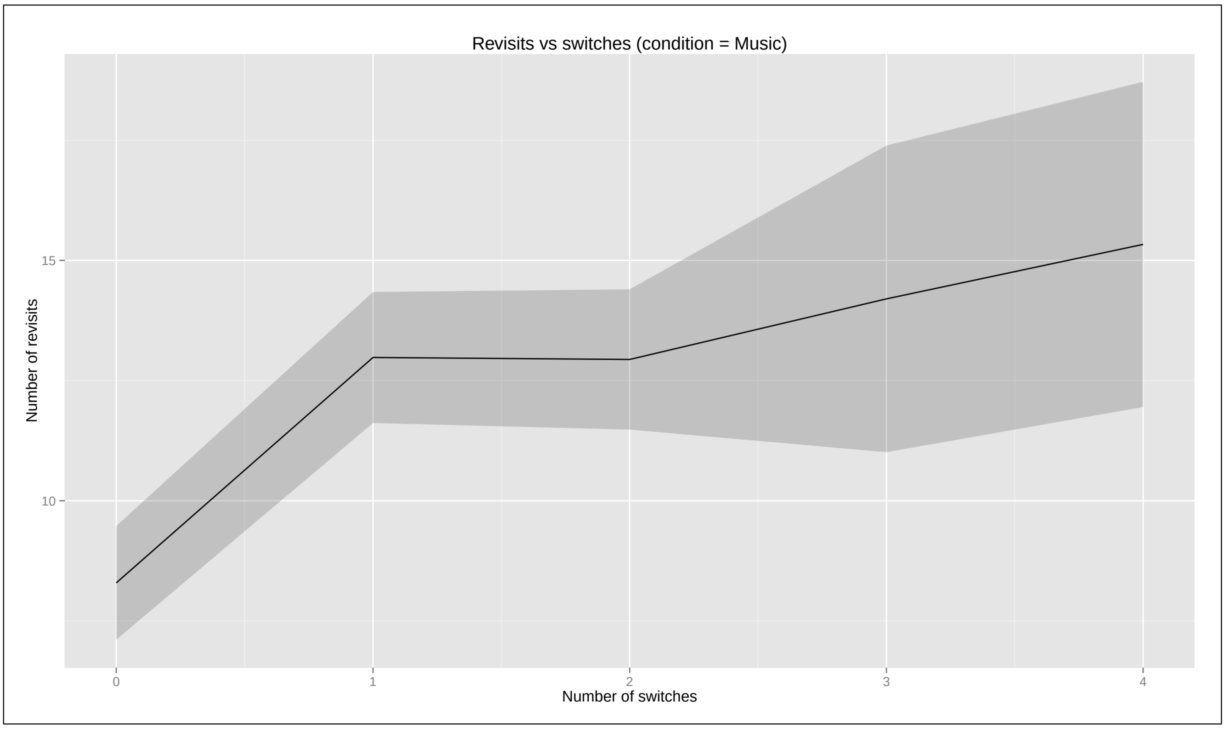

Figure 3: Number of revisits against number of switches per concentration block for the music condition

concentration card values during the music fragment quiz or n-back. It is likely that most subjects did some working memory rehearsal just before they made the decision to switch.

The results of Taatgen's and Katidioti's experiment, on the other hand, suggest something else. According to their data, there was no difference in performance between the forced and voluntary conditions. The amount of revisits did not significantly differ. This indicates that there was no extra rehearsal in the voluntary case compared to the forced condition. Because subjects could not make the switching decision in the forced condition, they could not rehearse before the switch. This implies an absence of a rehearsal period in the voluntary condition.

4.3 Secondary task preparation

Preparation for the second task could possibly have caused pupil dilation. Notice there is a subtle difference between preparation for a task and the change of goal. A change of goal is only an adaption of an internal goal without any extra preparation, whereas secondary task preparation is a more intensive cognitive process. It is a cognitive difference between 'okay, let's *do* this' and 'let's get *ready* for this.'

Secondary task preparation is probably not a factor to which dilation of the pupil can be addressed. We can explain this by referring to Taatgen's and Katidioti's experiment another time. In the voluntary condition with delay, the pupil size increase was shown at the exact same temporal location as in the voluntary condition without delay. When dilation of the pupil really showed preparation for the task to come, the pupil size peak would have been shifted to the right in the delayed condition. To ensure secondary task preparation is not one of the causes of pupil dilation before the switch, an experiment with the same conditions but with a constant delay should be performed. A variable delay can cause a participant to prepare yet before the switch, due to uncertainty regarding secondary task onset.

4.4 The pressing of a mouse button

The final explanation - aside of the decision-related factors - is a possible effect of the pressing of a mouse button (which initiated the switch) on the pupil size. This factor can never be ruled out, although it is very unlikely that a simple press of a button is responsible for the complete increase in pupil dilation: the pupil size peak is very large and is being build up over an interval of many seconds.

4.5 Conclusion

We can not just forget about the four factors mentioned above and address dilation of the pupil entirely to the decision itself. The arguments do suggest that the change of goal, rehearsal, secondary task preparation and pressing of a mouse button do not have caused the complete increase in pupil size, but the arguments are all based on a single experiment which was not even set up to test these possible effects. The rehearsal argument, for example, is not very direct and needs further testing. There is a hiatus concerning the argument about secondary task preparation, too.

The current research, combined with Taatgen's and Katidioti's, however, is a step towards a complete explanation of pupil dilation during sequential multitasking. Even a condition involving a minimal amount of planning, still showed a 2.5 percent increase in pupil size. It seems more and more likely that the decision itself plays a major role in this.

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