Effect of Post-Encoding Task Difficulty on Episodic Memory Consolidation

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Abstract

Decades of memory research have shown that memories are acquired in a fragile state and are strengthened over time, a process called consolidation. The research focused on the process of consolidation and what benefits and harms it. It was believed that rest and sleep are most beneficial for the consolidation of memories, but recently there have been studies showing that not all mental effort interferes with the quality of the consolidation. Autobiographical thinking might harm the process by introducing novel episodic memory processing while a 2Back task might suppress this phenomenon while not draining the episodic memory resources. In this study, we used a modified 0Back and 2Back delay period to ascertain how memory performance would be affected by different task difficulty and consequently different quality and quantity of thoughts. Participants went through an encoding period, where they learned faces, followed by the delay period, and lastly, a memory test was administered. Thought propensity was measured by random thought probes during the delay period. We hypothesized task-related thoughts to be associated with the 2Back condition and task-unrelated thoughts with 0Back. Furthermore, we expected similar memory performance in the two conditions. Our results showed that there were significant differences in the types of thoughts the frequency of them in the two conditions. Adding to that, 2Back memory performance was positively correlated with task-related thoughts. In conclusion, our results suggest substantial differences in types of thoughts between the conditions and relation between task-related thoughts and memory consolidation.

General Introduction

The way we, humans, make memories has been a central topic for thousands of years for philosophers, scientists, as well as for everyday conversations. From ancient Greece, where Plato compared memories to a wax tablet ingrained in the souls of humans (Theaetetus) to the beginning of experimental psychology where Georg Müller believed that mental processes are caused by physical developments in the body and that therefore memory in all its facets has to be governed by appropriate laws (Lechner, Squire & Byrne, 1999). Understanding memory in humans is of utmost importance as it influences every aspect of society, be it law and order – understanding the reliability of eyewitness testimonies, or education – spaced learning patterns in school teachings.

Memory Consolidation

Müller and Pilzecker (1900) proposed that memories are not stored instantly but, on the contrary, take time to be established and their form is not permanent. This process was coined "Konsolidierung" (consolidation) and suggests that memories are malleable after a period of learning. Specifically, Müller and Pilzecker asked subjects to memorize paired-associate nonsense syllables and subsequently asked the experimental group to memorize an intervening list of pairs whereas the control group was not presented with a second list. The memory test occurred after the second list was memorized (Müller & Pilzecker, 1900). They found that learning other information after an initial learning phase led to the first learned word-pairs memory being disrupted thus suggesting that memories are acquired in a fragile state and are strengthened over time through the process of consolidation (Müller & Pilzecker, 1900; McGaugh, 2000). Neurobiological studies have shown evidence for the consolidation process through functional MRI studies. These indicate continuous neural activity related to encoding, which occurred automatically in the post-learning period. Furthermore, the amount of neural activity showed a positive relation to memory performance, meaning the neuronal activity might arise due to a mechanism with which memories are strengthened – memory consolidation (Schmidt et al., 2006). Tambini et. al. (2006) found that BOLD (blood oxygen level-dependent) fluctuations occur depending on experience and are related to memory. This supports theories of memory consolidation positing a mechanism of storing memories in long-term memory through communication between the hippocampus and cortical areas. To this day memory research follows the acquired guideline that memory strengthening is dependent on time and interferences during consolidation.

As of today, we determined that the hippocampus is integral for the initial encoding of memories. At the same time, communication between the hippocampus and neocortical areas is responsible for the long-term storage as well as reformation of memories (Nadel, Samsonovich, Ryan & Moscovitch, 2000; Alvarez & Squire, 1994). Considering the aforementioned theories, memory consolidation nowadays is considered a process by which the brain stabilizes memory traces, which occurs at two stages: 1) early (minutes and hours) as a replay of neuronal firing patterns that took place during the learning experience causing the strengthening of the connection between memory features at a hippocampo-cortical level, and 2) gradually (across days and years) across the cortico-cortical level (Dickelmann & Born, 2010). To sum up, new learning experiences are replayed by the brain's neurons slowly solidifying the memory trace through communication between the hippocampus and cortical areas. Subsequently, this process moves more and more to a communication between the cortical areas and becomes more independent of the hippocampus.

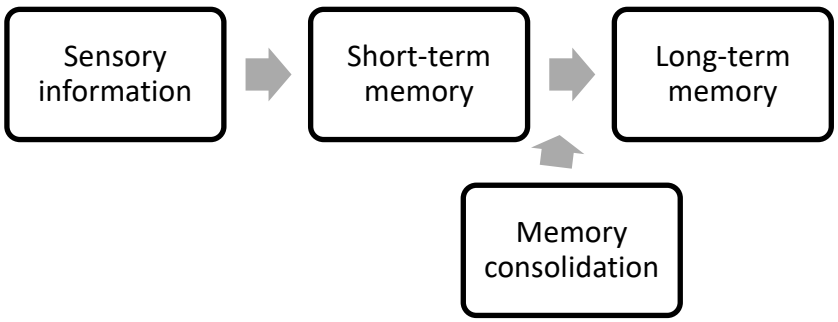

Figure 1. Memory acquisition process where sensory information is stored as short-term memory. Subsequently, memories are transported from short-term memory to long-term memory through the process of memory consolidation.

With this knowledge, research moved on to investigate the effect of mental states and activities on memory consolidation.

Mental Effort Hypothesis & Retroactive Interference

There has been extensive research positing that rest and sleep are most beneficial to the consolidation process. Craig, Sala & Dewar (2014; 2007) found that wakeful rest in a post-learning delay period lead to better memory performance in patients with severe amnesia compared to participants engaging in cognitive tests. This evidence was also found in healthy

subjects when performing mental arithmetic, spot-the-difference and tone-detection tasks. These results support the *mental effort hypothesis* which suggests that the absence of mental effort in the initial post-learning period benefits initial memory consolidation and subsequent memory performance. The beneficial nature of rest on consolidation is believed to arise due to a) the lack of *retroactive interference* - novel episodic memory processing that lays high demands on the same episodic memory resources necessary for on-going consolidation (Drosopoulos, S., Schulze, C., Fischer, S., & Born, J., 2007) and b) the reactivation of the neuronal pathways of the memory trace. For example, Dewar, Cowan & Sala (2009) compared a memory of items learned before a quiet rest period to those learned prior to equally long irrelevant tasks, like mental arithmetic, spot-the-difference task, etc. Regardless of the tasks, the memoranda, and type of memory tests, they found a consistent benefit of the rest condition over any post-learning task. Dewar, Alber, Butler, Cowan, & Della Sala (2012) also demonstrated in their study that this sort of enhancement was retained over a 7 days. These studies showed that post-learning activity interferes with the consolidation process whereas post-learning rest benefits it.

The aforementioned studies show that mental effort in the post-learning period affects memory consolidation and subsequent performance negatively through retroactive interference. Following this line of thinking, any mental activity, task-related or task-unrelated, should have a detrimental effect on memory performance when occurring after an initial learning phase. This should apply to thoughts, be it about images, past or future planning, other memories.

Mind-wandering is the experience of entertaining multiple strings of thoughts, which can occur in any situation to differing degrees. Autobiographical thinking, cued with familiar sounds such as a cat's meow, was found to decrease memory performance of prior learned material. This was not the case when familiar sounds were exchanged for meaningless ones (Craig, Sala & Dewar, 2014). Adding to the mental effort hypothesis, activity associated with the consolidation process may not deteriorate ongoing consolidation. Roediger & Butler (2011) indicated that retrieval or rehearsal might be beneficial to long-term memory retention. The benefit of rest for memory performance may arise partly due to rehearsal or focus on task-relevant stimuli when compared to cognitive tasks. These thoughts may be suppressed through specific tasks, such as n-back tasks, which may lead to a bettering of memory performance. This could be the case as autobiographical thinking uses the same resources as the consolidation process (Craig, Sala & Dewar, 2014).

Autobiographical thinking & Mind-wandering

However, due to the complex nature and wide-spread brain activity involved in the tasks used in the aforementioned studies, the exact aspects of these tasks that cause interference to memory consolidation remain unclear. Recently, in a similar task design, Varma et. al. (2017) used a modified 2-back task, which draws upon the brains executive functions (as opposed to episodic memory functions), as a comparison to a wakeful rest condition and found no significant difference in memory performance between the two. In another study, Varma, Daselaar, Kessels & Takashima (2018) also compared an autobiographical thinking condition with the previously mentioned rest and 2-Back conditions and found that autobiographical thinking led to a lower memory performance than in the 2Back and rest conditions. One of the reasons for these findings may be for example due to the suppression of off-task thinking, like autobiographical thinking, in the 2-back task. As a result, novel episodic processing is limited, and subsequently, interference with the consolidation process is reduced. This would explain similar levels of performance as the rest conditions would include a certain amount of thinking which includes novel episodic processing. This in turn decreases memory performance, considering that post-learning activities interfere with memory consolidation and rest allows for the reactivation of the neuronal pathways of the memory trace. According to the above-mentioned studies, not all mental effort necessarily interferes with memory consolidation. The mechanisms underlying such suppression during the 2-back tasks are an object of this study.

Summary & Aim of the study

To sum up, memories are believed to be acquired in a fragile state and are strengthened through the process of consolidation. During ongoing consolidation, memories are suspect to detrimental effects through retroactive interference. It was hypothesized that any mental effort interferes and has negative effects on the strengthening of memory traces. Recently, it has been assumed that rehearsal or task-relevant thoughts may have a positive impact on memory performance by suppressing autobiographical thoughts during rest which drains the same episodic memory resources as the consolidation process. The 2-back task has been assumed to suppress autobiographical thinking due to the task difficulty and the need to focus on the task. Due to the mentioned hypotheses in this paragraph, it is relevant to determine how a difference in thought propensity and frequency affect memory consolidation

and therefore memory performance. Different n-back tasks (such as 0-back and 2-back) have different task difficulty and allow for a different amount of mind-wandering which in turn would affect memory performance.

This study aims at investigating memory performance as a function of task difficulty and mind-wandering propensity. Task difficulty will be ascertained through two conditions, namely through the administration of a 0-back and 2-back task, while mind-wandering content and frequency will be measured through random-probe experience sampling during the two tasks. The potential findings could shed light on the mechanism of the suppression of interference by the n-back task by modulating task difficulty. The difference in task difficulty may affect the content and frequency of mind-wandering by which memory consolidation is influenced.

Therefore we will identify the relationship between memory performance, task difficulty, and mind-wandering. We will compare the nature and frequency of the thought probes in the two "task difficulty conditions" and how this affects memory performance after the experimental sequence. We are planning on identifying this relationship by adapting the experiment used in Varma, Daselaar, Kessels & Takashima (2018). The thoughts were monitored at the end of three encoding and delay periods, making the accuracy of the questionnaire results not as accurate as desired. Therefore in this experiment, we implement (pseudo)random experience sampling probes. Here on average every 30 seconds, the participant has to report the thoughts occurring before the moment of the probe. This allows for more accurate and on-time sampling of the thoughts. We are using 0Back and 2Back as the task difficulty and need to focus are assumed to be quite different. Due to the high vigilance and focus needed for the 2Back task, mind-wandering should not occur as much as in the 0Back task. The general experimental process starts with the encoding of faces, followed by the delay period consisting of either 0Back or 2Back, and lastly ends with the recognition task of the learned faces in the encoding face (Figure 2).

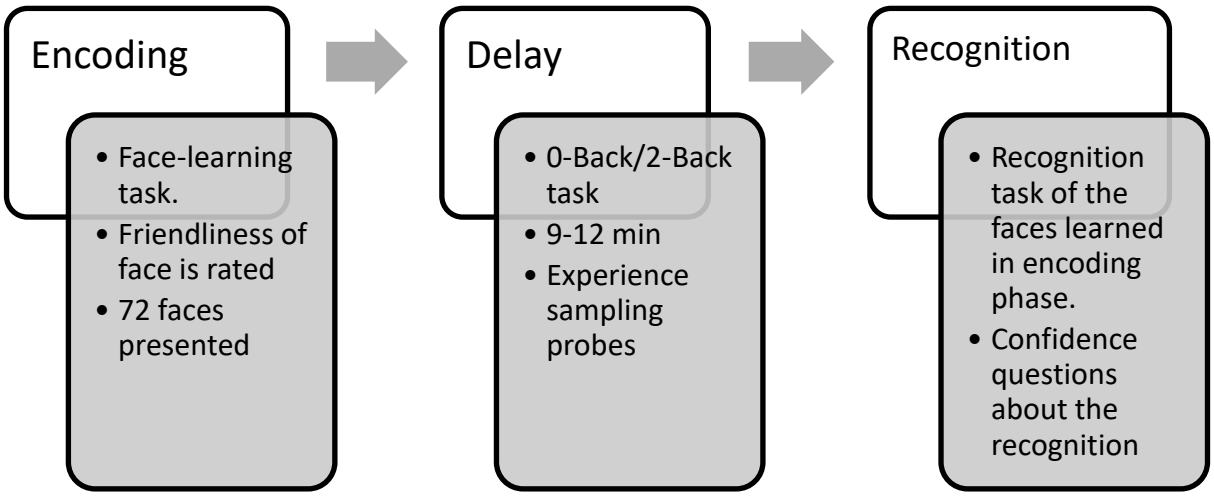

Figure 2. The experimental process used in the experiment. An initial encoding task where faces are presented and rated on friendliness, followed by the delay period which is comprised of either a 0Back or 2Back task with experience sampling probes emerging on the screen. The design is rounded off with a recognition task and confidence questions.

Hypotheses

The following hypotheses were built through consideration of previous theories and to shed light on gaps in current literature.

(1) We expect that task-related thoughts correlate with 2Back memory performance while task-unrelated thoughts correlate with 0Back memory performance.

Due to the previously mentioned theories and hypotheses, we would expect task-unrelated thoughts to be closely related to 0Back performance as they would appear more often and would interfere with the memory consolidation process. On the other hand, we would expect task-related thoughts to be closely related to 2Back performance as they would appear more often and would not be detrimental to the memory consolidation process.

(2) We expect memory performance to be similar, with no statistically significant differences, between the two conditions, namely 0Back and 2Back.

This hypothesis is grounded in the assumption that, like the rest condition in previous studies, the 0Back task might lead to less retroactive interference by other mental effort compared to the 2Back condition. On the other hand, the demands of the 2Back task might lead to a reduction in task-unrelated thoughts such as autobiographical thinking. Therefore,

the 0Back condition would allow for more neuronal reactivation of the memory trace and strengthen the trace and subsequently improve memory performance. At the same time, the 0Back condition would allow for more mind-wandering, such as autobiographical thoughts which would limit the processing resources needed for consolidation. On the other side, the 2Back condition would benefit from a reduction of task-unrelated thoughts which would benefit memory performance. These effects are expected to be balanced out over the whole experiment.

(3) We expect significantly more task-unrelated thoughts in the 0Back condition compared to the 2Back condition

This hypothesis is grounded in the assumption that due to the relative ease of the 0Back task, thoughts are more likely to wander off during the delay period whereas in the 2Back condition the focus on the task would substantially reduce off-task thoughts. Therefore we would expect to see higher on-task thoughts and less off-task thoughts in 2Back and vice versa with the 0Back condition.

Methods

Design

The experiment consisted of two sessions, session 1 and session 2, which were separated by a minimum of 1 and a maximum of 3 days. We chose a within-subjects design which was comprised of one dependent variable, namely memory, and two independent variables, the proportion of off-task thoughts and task difficulty through the two conditions – 0Back and 2Back. The conditions will be counterbalanced to be able to control for their effect. Within each of these conditions, participants' thoughts will be measured using probe questions. The main manipulation in this study is the difficulty of the n-back task. The encoding phase is comprised of a total of approximately 72 faces for which participants indicate perceived friendliness. The recognition phase contained faces of faces present in the encoding phase as well as new faces, where participants had to indicate if the face was seen before or not and how confident they were about the decision.

Participants

Participants were recruited online through e-mails and were between the ages of 17 and 28. A total of 33 participants conducted the experiment excluding possible outliers and excluded cases. 7 participants were excluded due to technical or organizational problems in the experiment (failure to load experiment, performed 0Back twice). The analysis was performed after outlier removal which was conducted as follows. We excluded 2 participants due to performance on n-back tasks which were more than 1,5 standard deviations from the standardized z-scores. One participant was excluded due to n-back performance as well as due to relative non-responsiveness during the experience sampling probes. Lastly, the last participant was excluded due to grave issues in the encoding phase. This led to the removal of 4 participants leading to a final sample size of 24 participants. The number of 36 participants was tried to be achieved due to the fulfillment of statistical power as mentioned in Varma, Takashima, Krewinkel, van Kooten, Fu, Medendorp, Kessels & Daselaar (2017). Voluntary participation in the experiment is a possibility while compensation will be provided in the form of money or credits. The minimum compensation in case of non-completion of the experiment is €0,00/1 credit for up to 15 minutes and €3,50/1credit for up to 30 minutes. The compensation for a completed experiment amounts to €7,00 or 2 credits.

Procedure

A JavaScript version of the PsychoPy experiment was hosted on an online repository called Pavlovia.org. Participants received a link via their personal or SONA email to start the experiment. In total, the study takes up to 60 minutes for a participant to complete, divided into two days; 30 minutes on day 1 and 30 minutes on the second day. Participants start with executing a face-learning task, followed by a 9-12 minute delay period involving 0-Back or a 2-Back task in a counterbalanced order. During these delay periods, experience-sampling probes will be presented approximately every 30 seconds asking participants to categorize the nature of their thoughts before the interruption (e.g., thoughts about learned material, task, personal concerns, etc.). We do not query or record the content of these thoughts. At the end of the delay period, a recognition memory test will be administered to test face-recognition memory. On the pre-arranged day 2 of the experiment (taking part within 3 days after day 1), participants complete the same tasks in the second condition. All aspects of this experiment- including the recognition tests- will be run online. Participants are debriefed and can be compensated at the end of the experiment.

Materials

Encoding stimuli

During the encoding period, a total of 72 faces were presented visually. Participants rated the friendliness of the face on a scale from 1 to 4 (“surely unfriendly”, “unfriendly”, “friendly” and “surely friendly”).

N-back task

Following the encoding session, a delay period of either 0Back or 2Back lasting 9-12 minutes, was administered. Both 0Back and 2Back tasks show a running sequence of numbers ranging from 1-5, displayed in random order. For 0Back, instructions were given to press the “right” key solely if the currently displayed number is a ‘3’, or “left” key if any other number was shown. For 2Back, instructions were given to press the “right” key if the number displayed was the same as two trials earlier, or press the “left” key if this was not the case. In both conditions short feedback was shown, in the form of the number turning green or red, for each trial, indicating the correctness of the response. The feedback was intended to raise motivation to be more attentive towards the task (Varma, Daselaar, Kessels & Takashima, 2018).

Experience sampling probes

This study used a random-probe experience sampling method to determine the content and frequency of thoughts during the experiment. The following questions will be included in the probe: (1) Blank/no particular thoughts, (2) Distracted by pain, sounds, etc., (3) Focused on the task, (4) Thinking how well you're doing at the task, (5) Thinking about the learned faces, (6) Knowingly thinking about personal stuff, (7) Unknowingly thinking about personal stuff. The questions will appear on the screen at (pseudo-)random instances. The purpose of the questionnaire was to assess 1.) the proportions of off and on-task thoughts in the two conditions, 2.) the difference in frequency of thoughts in the two conditions while expecting to have more off-task thoughts in the "lower task-difficulty" condition (0Back). On-task thoughts were defined as the proportion of "focused on task" answers the participant indicated during each condition. Off-task thoughts were defined as the grouped proportion of "Knowingly thinking about personal stuff" and "Unknowingly thinking about personal stuff" answers the participant indicated during the two conditions. Lastly, four categories which don't fall into the aforementioned categories were coined "Focus on performance", „Blank", "Distracted" and "Rehearsal". To sum up, participants indicated for each delay period the proportion of thoughts corresponding to one of the categories described above.

Memory Performance

Memory performance is measured by a simple recognition task, where participants have to indicate if they remember a face shown to them at the beginning of the experiment. The d-prime, which represents memory performance, is calculated by taking the standardized difference between the hit rates (proportion of correctly recognized faces) and false alarm rates (proportion of wrongly recognized faces).

Analyses

We only included "high confidence" responses (cHigh) in the analysis to measure recollection memory without the influence of familiarity. Based on the hypotheses stated in the introduction of this thesis we performed a repeated-measures ANOVA with the 2 conditions (0-back vs 2-back) as a within-subject factor using high-confidence d-prime as dependent variables. The order was added as a between-subject factor ("2BackEnd" and "0BackEnd") to ascertain if the counterbalancing was effective and if memory performance was affected by the factor. We will perform a dependent-samples t-test on memory performance between the two conditions (0-back vs. 2-back) in case the order is not

significant to confirm the results of the RM-ANOVA. Furthermore, we will conduct Pearson correlation tests on the relationship between memory performance within each condition and the degree of off-task thoughts during the condition for variables that have a normal distribution. While with non-normally distributed variables we will use spearman's correlations. We investigated through paired-samples t-test if there was a significant difference in the proportions of the ESP results between the two conditions. All results reported were calculated with the IBM SPSS 20 software where alpha was set at 0.05.

Results

Memory performance between the conditions

Memory performance scores, reported as d-prime, were as follows for high confidence: 0Back: *M* = 2.09, *SD* = .82; 2Back: *M* = 2.28, *SD* = .77.

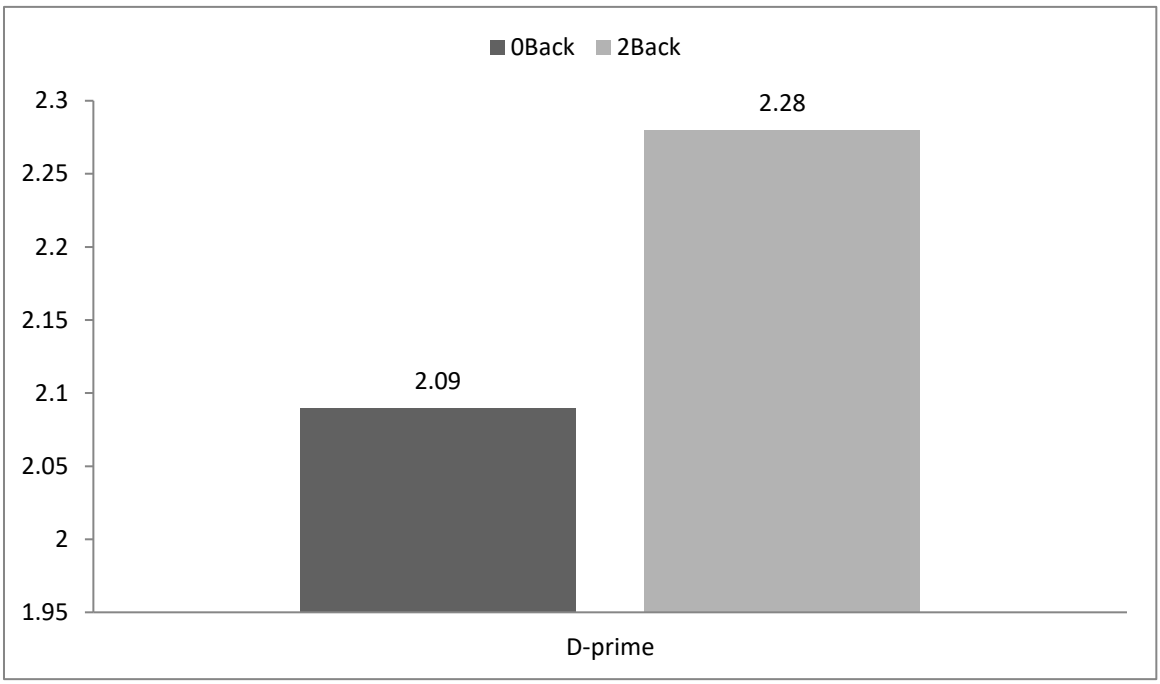

Figure 3. Mean scores of memory performance, as measured by d-prime, between 0Back and 2Back.

A repeated-measures ANOVA determined that mean d-prime scores did not differ significantly across the two conditions ($F_{(1, 20)}$ = 1,994, p = .173). This indicates that memory performance did not differ depending on the delay period. In the analysis, we observed a trend towards order being significant ($F_{(1, 20)}$ = 3.640, p = .071). Participants who completed the 2-back task at the end (B2End) had a tendency to perform better (Mean Difference = .563, p = .071). Therefore, we can conclude that the results for the ANOVA did not indicate a significant effect for task difficulty as measured by the n-back conditions.

Due to order not playing a statistically significant role the conditions were compared in a paired samples t-test. Here the results of the previously administered RM-ANOVA were confirmed ($t_{(21)}$ = -1.396, p = .177). These results support the second hypothesis mentioned in the introduction of similar memory performances between the two conditions.

Task-unrelated & task-related thoughts in the conditions

Next, we investigated how memory performance was affected by the thoughts which occurred during the delay period of the experiment. Here we used Experience sampling scores which were coded in the following way: On-task proportion (a proportion that was related to on task thought), Off-task proportion (a proportion that was related to intentional and unintentional personal thoughts). To assert which correlation test to use we tested if our variables were normally distributed. A Kolmogorov-Smirnov test indicated that off-task thoughts in both conditions do not follow a normal distribution ($D(22) = .186$, $p = .046$ for 0Back; $D(22) = .452$, $p = .000$ for 2Back) whereas on-task thoughts in both conditions followed a normal distribution ($D(22) = .101$, $p = .200$ for 0Back; $D(22) = .151$, $p = .200$ for 2Back). The results suggested that in both conditions the on-task thoughts were normally distributed and therefore were investigated with Pearson's correlation while on the other hand the off-task thoughts were investigated with Spearman's correlation.

Pearson Correlations showed a statistically significant value for on-task thoughts in the 2Back condition ($rp(22) = .471$, $p = .013$). For the 0Back condition on-task thoughts didn't correlate significantly with the memory performance ($rp(22) = .031$, $p = .449$).

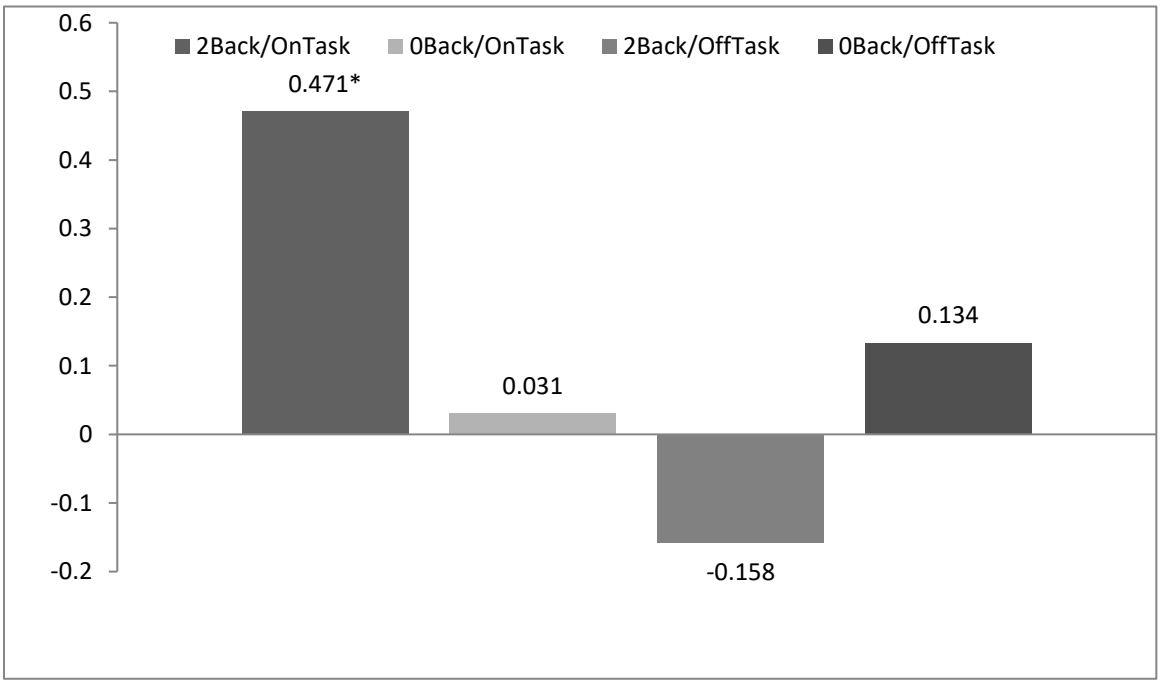

Figure 4. Correlational values of 1. OnTask thoughts and memory performance in 2Back condition, 2. OnTask thoughts and memory performance in 0Back condition, 3. OffTask thoughts and memory performance in 2Back condition and 4. OffTask thoughts and memory performance in 0Back condition. (* → $p < 0.05$).

Concerning the Spearman's correlations both 2Back off-task thoughts (rs = .-158, p = .241) as well as 0Back off-task thoughts (rs = .134, p = .276) did not correlate with memory performance. These results partly confirm our first hypothesis of 2Back performance being associated with task-related thoughts whereas 0Back performance did not significantly correlate with task-unrelated thoughts. The general picture of the correlations is visible in Figure 4 where 0Back has more relation with task-unrelated compared to task-related thoughts while the contrary is observable in the 2Back condition. Thus, we can conclude that only on task thoughts has a significant positive relationship with memory performance in the 2Back condition.

Type and frequency of thoughts in the conditions

We investigated the proportions of thoughts the participants had in each delay period to see if there were substantial differences in the type of thoughts and frequency of thoughts depending on which delay period we inspected. In both delay periods, we observed that *FocusOnTask* was the most prevalent type of thought, while this seemed to occur substantially more in the 2Back condition (64% vs. 46%). The contrary applies to the off-task thoughts where the 2Back condition shows less off-task thoughts (5% vs. 21%). Figures 4 and 5 show the whole distribution of thought proportion in each condition.

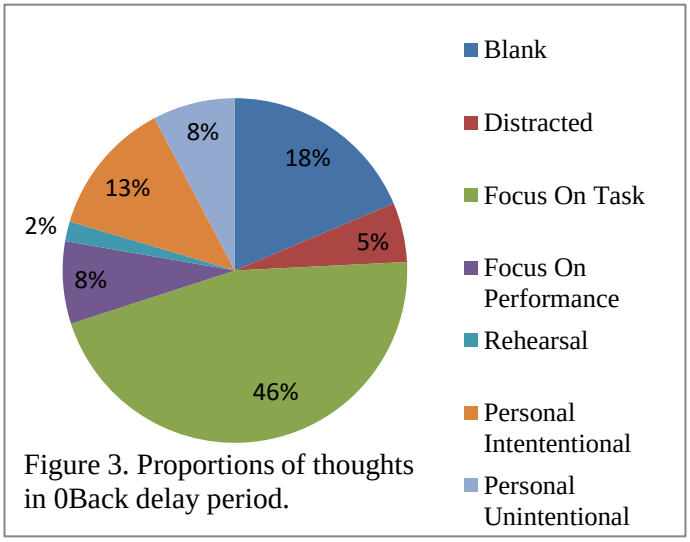

Figure 3. Proportions of thoughts in 0Back delay period.

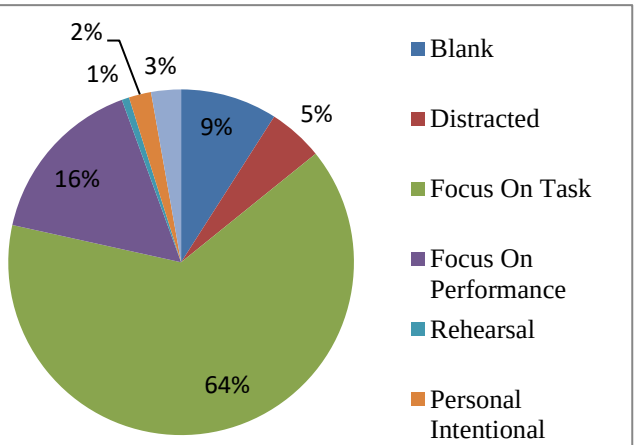

Figure 4. Proportions of thoughts in 2Back delay period.

Due to the high differences in frequency of thoughts we performed a paired-samples t-test on the types of thoughts between the two conditions. We observed a statistical difference between the conditions in on-task thoughts as well as in off-task thoughts ($t(21) = -3.000$, $p = .007$ for on-task thoughts; $t(21) = -5.216$, $p = .000$ for off-task thoughts). The results show that in the 2Back condition participants had substantially more on-task thoughts whereas in the 0Back condition participants experienced more off-task thoughts.

Discussion

Multiple studies dating back to the early 20th century have shown that memory is fragile and consolidated over time. These insights led to multiple theories and experiments trying to illuminate the mechanisms affecting the consolidation period and which effects are beneficial or detrimental to memories being formed. Sleep and rest have been posited as most beneficial due to limited interference in the consolidation process which led to better memory performance (Craig, Sala & Della, 2014). Accordingly, all mental effort after a learning period harms the consolidation process and therefore memory performance. Recently the view that not all post-learning activity interferes with the consolidation of memories started to emerge (Varma, Daselaar, Kessels & Takashima, 2018). This means only activities that rely on the same episodic memory processing capacities would interfere with the consolidation and affect memory performance negatively. Therefore, thoughts that are had by people after learning, affect the quality of consolidation, and can give information on how retroactive interference benefits or harms memory performance. In this study, we aimed at understanding how the difference in quality and quantity of thoughts as modulated by task difficulty would influence memory performance. To test this hypothesis we conducted a within-subject experiment investigating memory performance in two conditions, namely 0Back and 2Back, and recorded type and frequency of thoughts by the participants to establish differences in the conditions and if these differences affect memory.

Findings of the study

The results indicate that memory performance between 0Back and 2Back conditions did not differ statistically. Thus, participants did not differ depending on the post-learning delay period. The study demonstrated a positive correlation between task-related thoughts in the 2Back condition and memory performance. Therefore, the more participants had task-related thoughts the better the memory performance was in the 2Back condition. Furthermore, the analysis confirmed that the two conditions differed significantly in types and frequency of thoughts. The 0Back condition demonstrated considerably more task-unrelated thoughts than the 2Back condition while task-related thoughts were more abundant in the 2Back condition. Adding to that, the experience sampling probes revealed that in the 0Back condition participants experienced more of multiple different types of thoughts including distraction, intentional or unintentional mind-wandering, and a general blank state as well as rehearsal.

Integration of findings

Previous studies have shown that 2Back delay periods led to similar memory performance when compared to a wakeful rest condition while autobiographical thinking (ABT) led to lower memory performance (Varma, Daselaar, Kessels & Takashima, 2018). We hypothesized to arrive at a similar result as the 0Back condition is similar to the rest condition used in the aforementioned study in terms of occurrence of task-unrelated thoughts and more room for the reactivation of neuronal pathways. Task-unrelated thoughts, such as autobiographical thinking are assumed to use the same episodic memory resources which would lower the quality of consolidation through retroactive interference and consequently harm memory performance. On the other hand, the 2Back task does not use episodic memory processing and requires considerably more focus on the task and would allow for fewer distractions which following the same logic would lead to better memory performance. In line with the hypothesis memory performance in both conditions was similar.

The observed association between 2Back memory performance and on task thoughts was in line with the hypothesis. The results showed a positive association between 2Back memory performance and task-related thoughts, meaning that the occurrence of more on task thoughts coincided with higher memory performance. This supports the view that performance on the memory recognition test is closely associated with the amount of task-related thoughts and subsequently the lack of task unrelated thoughts. It provides evidence for the theory that task-unrelated thoughts would reduce the quality of memory consolidation and therefore memory performance. On the other hand, we did not find a correlation between 0Back memory performance and task-unrelated thoughts. Results were contrary to the hypothesized relation where task-unrelated thoughts would be associated negatively with memory performance and had a reversed pattern in our study. These results could be explained by the design of the study (online) or the low sample size.

Supporting our hypothesis the data shows that the 0Back condition had substantially more task unrelated thoughts compared to the 2Back condition. This is in line with previous research where participants in a 2Back condition had low mind-wandering propensity while rest and ABT conditions showed substantially more task-unrelated thoughts (Craig, Sala & Dewar, 2014; Varma, Daselaar, Kessels & Takashima, 2018). While rest and ABT conditions are not directly comparable to a 0Back condition, the results indicate that it is due to the lower difficulty there were more chances for mind-wandering in the 0Back condition. These results build on this existing research leading to the conclusion that the type and frequency of

thoughts can be modulated by task difficulty in the form of the used modified 0/2Back tasks. When comparing types of thoughts and their frequency of occurrence in the two conditions we find that participants in the 2Back exhibited substantially more thoughts on the task and performance while participants had more thoughts about intentional and unintentional personal thoughts as well as the rehearsal of learned faces and a general blank state. This adds to the view that the 2Back task suppresses any task unrelated thoughts and leads to participants mainly concentrating on the task itself. Therefore the results show that the modulation by task difficulty can be used to ascertain the difference in quality and quantity of thoughts during a post-learning delay period.

Significance of the findings

The results build on existing evidence of Varma, Daselaar, Kessels & Takashima (2018) where the researchers found that 2Back memory performance was comparable to a rest condition and superior to an autobiographical thinking condition. Furthermore, it expanded on their findings that a 2Back delay condition would generate substantially more task-related thoughts than quiet rest and autobiographical thinking conditions. Our results show that this extends to the modified 0Back task used in this study. Therefore it validates the use of 0Back and 2Back conditions as a modulator of task difficulty. Adding to that, we found that task-related thoughts and memory performance in the 2Back condition were positively related. This supports the view that even though the 2Back task might limit automatic reactivation, the benefits for consolidation might arise from the reduced chances of interference from task-unrelated thoughts in combination with the non-episodic nature of the task. The experiment provides new insights into the modulation of memory performance through 0Back and 2Back (task difficulty) and lays the groundwork for further online studies using the delay conditions and experience sampling probes.

Limitations

Firstly, the need to perform neurobiological studies on a comparable study design exists to determine if mind-wandering propensity and frequency are neurobiologically affecting the process of ongoing consolidation in the way assumed in this study.

The main limitation is that the sample falls short of the required sample size as indicated by power calculations before the study. Therefore the reliability of this data is impacted by the insufficient amount of participants and all results should be interpreted with

this in mind. Nonetheless, we invested in neutralizing any confounds related to the order, health, or education through for example counterbalancing to formulate our analysis.

Additionally, due to the study being performed online there was no full control for environmental influences that may have appeared, such as distractions, noises, etc. which all could affect the data. Therefore we cannot completely rule out the possibility that interference during the study came from external stimuli.

Future research

Future research can adopt the online study design as a template while correcting the aforementioned limitations as much as possible. The addition of another gradient of task difficulty would shine more light on the manifestation of the influence of task difficulty on memory performance. Additionally, this study design could be adopted for laboratory designs and improved on for neurobiological research to be possible. The study was designed with a possibility of including future neurobiological, such as pupil diameter measurements, into the design.

Conclusion

As the first online version of this paradigm of memory consolidation research to our knowledge, we established that the study design is valuable to inspect memory consolidation. Due to limited statistical power, the results should be interpreted with caution and further studies are necessary. We showed especially that 2Back memory performance was positively associated with task-related thoughts. Additionally, the results clearly showed that the modulation of task difficulty led to significantly different thinking patterns, including off task and on task proportions. These results may have affected memory performance leading to similar results in both conditions. Neurobiological studies would help shine more light onto the processes beneath memory performance as affected by task difficulty and task-related and task-unrelated thoughts.

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