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Effects of post-encoding wakeful rest and study time on long-term memory performance

Markus Martini, Caroline Martini, Thomas Maran and Pierre Sachse

Department of Psychology, University of Innsbruck, Innsbruck, Austria

ABSTRACT
Recent work shows that post-encoding wakeful rest, in contrast to a cognitive task delay period, supports memory performance. The present study aimed at investigating whether study time modulates the impact of post-encoding rest on delayed memory performance. Healthy young adults were allocated to one of two "study time" groups (fixed-paced vs. self-paced). Participants encoded two word lists. After immediate recall of one word list, participants wakefully rested for 8 min, after the other, they performed a visual problem solving task. A delayed recall took place at the end of the experimental session (Experiment 1) and again after 7 days (Experiment 1 + 2). We found that participants in the self-paced group outperformed those in the fixed-paced group. In Experiment 1, participants showed higher memory performances after 7 days in the resting condition independent of study time. No significant differences between post-encoding (rest vs. problem solving) and study time conditions were found in Experiment 2. Combined analyses of both experiments revealed that an additional recall (Experiment 1) supported memory retention in both post-encoding conditions. Our findings suggest that resting is beneficial over the long term, but only when the encoded information is repeatedly retrieved at the end of a learning session.

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Wakeful resting; interference; self-paced learning; memory consolidation; long-term memory

Introduction

Research suggests that the minutes to hours that immediately follow new encoding are influential for the subsequent retention of encoded information. Already Bigham (1894) showed that participants recalled less when the interval between learning and recall was filled by cognitively demanding activities, in contrast to an "unfilled" interval leading to less memory errors. Müller and Pilzecker (1900) found that a longer temporal separation (6 min) between two word lists increased participants' memory performance for the first word list, while a shorter temporal separation (36 sec) decreased memory performance for the first list, also when a visual distractor task was applied after learning. Recent studies with varying stimulus material, post-encoding activities, and recall intervals support the view that a brief period of post-encoding wakeful rest, in contrast to a cognitive task delay period, supports memory retention over shorter (minutes) and longer (days) time intervals (Cowan, Beschin, & Della Sala, 2004; Craig, Dewar, Della Sala, & Wolbers, 2015; Della Sala, Cowan, Beschin, & Perini, 2005; Dewar, Alber, Butler, Cowan, & Della Sala, 2012; Dewar, Cowan, & Sala, 2007; Mercer, 2015; but see Martini, Riedlsperger, Maran, & Sachse, 2017; Varma et al., 2017 for recent conflicting findings).

Explanations for the beneficial effect of a brief period of wakeful rest after learning can be found in interference and consolidation theories. Interference theories assume that memories interfere with each other resulting in decreased memory performance. For instance, temporal distinctiveness theory proposes that information that is processed in temporal proximity to the to-be-remembered information impairs its retrieval, while temporal distance retrieval improves retrieval by inducing temporal distinctiveness (see Brown, Neath, & Chater, 2007; Ecker, Brown, & Lewandowsky, 2015).

CONTACT Markus Martini markus.martini@uibk.ac.at

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Accordingly, resting after learning should support memory retention more than an interfering task (e.g. learning vocabularies), since encoding of new material after learning impairs the access to the previously learned memory content (Brown et al., 2007; Farrell & Lewandowsky, 2002; Müller & Pilzecker, 1900; Oberauer & Kliegl, 2006). Increasing the time interval between the to-be-remembered memory content and distracting information leads to lower interference and consequently higher memory performance (Brown, Morin, & Lewandowsky, 2006; Brown et al., 2007; Dewar, Garcia, Cowan, & Della Sala, 2009; Ecker, Tay, & Brown, 2015).

Similarly, consolidation theories (Wixted, 2004) state that memories are affected by interference after learning, but in contrast to interference theories, they are often neurophysiologically and neuroscientifically founded. It is assumed that new information takes time to stabilise, i.e. to be transformed into longer lasting memories less vulnerable to interference (Dudai, 2012; Robertson, 2012). The longer the temporal gap between information uptake and interrupting activity, the more consolidation can take place resulting in less forgetting and higher delayed memory performance (Dewar et al., 2007; Dewar et al., 2009; Wixted, 2004). Studies with animals and humans showed that forgetting occurs when consolidation is impaired through post-encoding interventions such as administration of neurotransmitters or hormones, electrical or magnetic stimulation and task-related mental processes (Dewar et al., 2007; Fischer & Born, 2009; for a review see McGaugh, 2015). The longer the temporal gap between information uptake and interrupting activity the more consolidation can take place resulting in less forgetting and higher delayed memory performance (Wixted, 2005). According to Dewar et al. (2007), forgetting can be induced not only by similarity between the to-be-remembered information and the interfering stimuli (e.g. learning verbal material followed by verbal interference), but any subsequent mentally effortful task, irrespective of its content (e.g. learning verbal material followed by non-verbal interference; e.g. spot-the-difference task; Dewar, Alber, et al., 2012). Studies showed that consolidation processes are associated with a post-encoding heightening of neural activity in brain areas that were also active during the learning process itself (Fell & Axmacher, 2011). The strength of the neural post-encoding rest activity is thereby positively related to the delayed memory performance (Tambini, Ketz, & Davachi, 2010), suggesting that it reflects a passive post-encoding "replay" of the previously learned content, which leads to memory stabilisation (Dudai, Karni, & Born, 2015). Passive replay has been shown to take place during sleep and states of wakeful rest (Deuker et al., 2013). Electrophysiological studies indicate that a replay during a state of sleep and quiet rest may even show similar oscillatory patterns (Brokaw et al., 2016).

The present studies

In the present studies, we aimed at investigating whether study time modulates the effect of a post-encoding study intervention. More specifically, we investigated differences in memory performance in a post-encoding resting versus problem solving condition, where the to-be-remembered information was presented in a fixed- versus self-paced rate. Evidence exists that study time has an impact on memory performance. For instance, studies investigating variations in fixed-paced stimulus presentation rates showed a non-monotonic relationship between presentation rate and recall performance (de Jonge, Tabbers, Pecher, & Zeelenberg, 2012; Zeelenberg, de Jonge, Tabbers, & Pecher, 2015). Thus, very slow and fast presentation rates resulted in worse memory performance compared to intermediate (4 sec) presentation rates (de Jonge et al., 2012; Zeelenberg et al., 2015). An increase in memory performance was also found under self-paced study time conditions, in which participants were allowed to freely allocate study time to increase control over their study behaviour (de Jonge et al., 2012; Tullis & Benjamin, 2011). A possible explanation of the memory supporting effect of prolonged/self-paced study time is that the encoded information has more time to get consolidated (De Schrijver & Barrouillet, 2017; Ricker & Cowan, 2014) and various strategic memory control processes like attentional refreshing, articulatory rehearsal, imagination, and grouping (Camos, Lagner, & Barrouillet, 2009; Groninger, 1971; Unsworth, 2016) as well as metacognitive strategies (e.g. monitoring, decision for and implementation of an effective study strategy; Tullis & Benjamin, 2011) can be applied to support its retention.

Our study design was based on a design used in similar previous studies (Alber, Della Sala, & Dewar, 2014; Craig et al., 2015; Dewar, Alber, et al., 2012; Dewar, Pesallaccia, Cowan, Provinciali, & Della Sala, 2012; Varma et al., 2017). In the present studies, each participant in the fixed-paced and self-paced condition was required to encode one word list followed by a resting condition, and the other word list followed by a problem solving condition. In the fixed-paced study time condition, words of the two word lists were visually presented one by one for 1250 ms (no inter-stimulus interval, ISI). The presentation duration was chosen based on existing wakeful resting studies (e.g. Dewar, Alber, et al., 2012: words of a story, 1 s/word; Dewar, Alber, Cowan, & Della Sala, 2014: word list, 1 s/word, ISI 2 s; Varma et al., 2017: words pais, 5 s/word pair, ISI 3 s) and studies investigating learning with verbal material (e.g. Engle & Roberts, 1982: 1.2 s/word; Jacoby, Shimizu, Daniels, & Rhodes, 2005: 1.5 s/word; Turkeltaub, Gareau, Flowers, Zeffiro, & Eden, 2003: 1.2 s/ per stimulus, ISI 3 s; Unsworth, 2016: words, 1 s, 4 s, self-paced/word, ISI 1 s). In the self-paced condition, participants themselves determined the presentation duration of each word of the word list. We chose a self-paced over a prolonged fixed-paced condition to allow participants more control over their study behaviour. After encoding each word list, an immediate recall took place. A wakeful rest period (eyes closed, relaxed) followed immediate recall of one word list, and a problem solving task period followed immediate recall of the other word list. At the end of the experimental session, a first delayed recall (Experiment 1) and a second delayed recall after 7 days (Experiment 1 and 2) took place, where participants were required to recall both word list.

Experiment 1

The first aim of Experiment 1 was to replicate previous findings that a mentally effortful task, here a problem solving task, compared to a brief period of wakeful rest (eyes closed, relaxed), diminishes delayed memory performance. Based on the findings discussed above (Brokaw et al., 2016; Craig et al., 2015; Dewar, Alber, et al., 2012; Dewar et al., 2007; Mercer, 2015), we assumed to find no differences in immediate memory performance between the two post-encoding conditions (rest, problem solving) and higher first and second delayed memory performance in the rest compared to the problem solving condition (Dewar, Alber, et al., 2012). The second aim was to test whether study time modulates the resting effect. Based on the findings discussed above (de Jonge et al., 2012; Tullis & Benjamin, 2011; Unsworth, 2016), we assumed to find higher immediate and delayed memory perfomances in the self-paced compared to the fixed-paced study time condition. We assumed to find a resting effect in the fixed-paced, but not in the self-paced condition based on assumptions that more stable memory representations seem to be less susceptible to interference over shorter and longer retention delays (Robertson, 2012; Roediger & Butler, 2011), and less stable memory representations are more vulnerable to interference immediately after their acquisition, in turn decreasing memory retention and subsequent memory performance (De Schrijver & Barrouillet, 2017; Wixted, 2005; Wixted & Cai, 2013).

Method

Participants

Fifty-six students (45 female, mean age = 22 years, age range 17–32 years) took part in the experiment in exchange for course credit. Participants were randomly assigned to one of two study time conditions.

Materials and procedure

Figure 1 illustrates the basic experimental procedure. We conducted a mixed factors design with recall time (immediate, first delayed, second delayed) and post-encoding condition (resting, problem solving) as within-subject factors, and study time (fixed-paced, self-paced) as between-subjects factors. Participants were required to (i) retain a first word list; (ii) immediate free recall the words of this list; (iii) perform an 8-min post-encoding condition, where they either rested wakefully or completed a visual problem solving task; (iv) retain a second word list; (v) immediate free recall words of this second list; (vi) perform an 8-min post-encoding condition, where they either rested wakefully or completed a visual problem solving task; and (vii) finally complete a first delayed free recall test for both word lists at the end of the experimental session and a second delayed free recall test for both word lists after 7 days in Experiment 1, and only one delayed free recall test after 7 days in Experiment 2. Participants were not informed about the delayed recall tests. Order of the two word lists and the post-encoding conditions were counterbalanced within both study time groups using 8 rotations (A1B1-A2B2, A1B2-A2B1, A2B1-

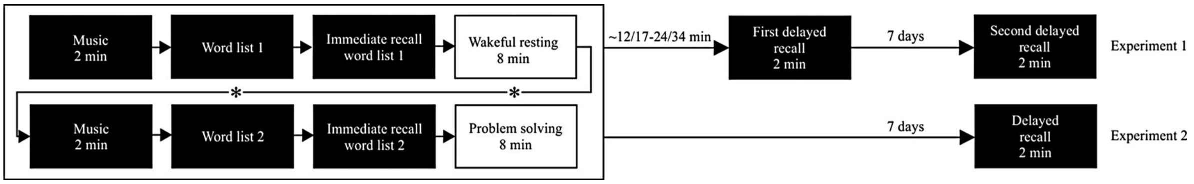

Figure 1. Experimental procedure. Participants learned two word lists. In the fixed-paced group words were presented for 1250 ms, in the self-paced group participants themselves determined the presentation duration of each word. The critical manipulation occurred after immediate recall of the respective word list. Participants either rested wakefully or solved problems (see Method section). In Experiment 1, a first delayed free recall test took place (fixed-paced condition: after 12–24 min; self-paced condition: after 17–34 min), and again a second delayed free recall test after 7 days. In Experiment 2, only one delayed free recall test took place after 7 days. Participants were not informed about the delayed recall tests. (*) = order of the word lists and post-encoding conditions were counterbalanced across participants.

A1B2, A2B2-A1B1; A = word list; B = post-encoding condition).

Two word lists were taken from the Verbal Learning and Memory Test (Helmstaedter, Lendt, & Lux, 2001). Each word list consisted of 15 mono- and bi-syllabic nouns. Words were semantically unrelated within the word list and between the word lists. Words were presented sequentially in the middle of the screen for 1250 ms in the fixed-paced condition. In the self-paced condition, participants themselves determined the presentation duration of each word of the word list by pressing the enter key. Participants in both study time conditions were instructed to retain the words as accurately and fast as possible for a following free recall test. In the immediate recall test, participants had 1 min to write down as many words, in any order they wanted, from the two previously presented word lists, as possible on a blank sheet of paper. After the immediate free recall, participants either rested wakefully or solved matrices for 8 min. In the rest condition, participants were asked to relax quietly with their eyes closed in the darkened testing room. In the problem solving condition, participants were required to solve abstract visuo-spatial problems taken from the Advanced Progressive Matrices (Set II; Raven, Raven, & Court, 1998). The matrices test is a paper-and-pencil measure of abstract reasoning and consists of 48 items (36 in Set II) presented in ascending order of difficulty. Each item consists of 9 geometric patterns. In the target pattern a part in the bottom right corner is missing. Participants have to select among eight alternatives the one that correctly fits into the missing part. The matrices had the advantage that through their progressive and challenging character participants' minds were continuously occupied throughout the whole length of the post-encoding interval. Additionally, solving mentally effortful matrices could well be demarcated from a resting phase. Following the respective post-encoding condition, participants were asked to answer the question whether they consciously rehearsed the previously learned words (Table 1). At the end of the experimental session (after ~30 min), a free recall test took place. Participants were instructed to remember as many words as possible from the previously presented two word lists and were given 2 min to write them down in any order they wanted on a blank sheet of paper.

After 7 days, participants were re-invited for a second experimental session. Participants were not told the purpose of the second experimental session. They only knew that the whole experiment consisted of two experimental sessions. In a free recall test, they were required to recall as many words as possible within 2 min from the two word lists presented 7 days ago. Participants noted the words on a blank sheet of paper.

Number of participants in the first and second experimental session varied between 1 and 4

Table 1. Descriptive statistics of the mean number of correctly recalled words and mean item responses to question on conscious rehearsal (Experiment 1).

		Post-encoding condition	
		Rest *M (SD)*	Problem solving *M (SD)*
Immediate recall	Fixed-paced	8.92 (2.61)	9.12 (2.58)
	Self-paced	13.00 (1.52)	13.35 (2.00)
First delayed recall	Fixed-paced	6.81 (3.06)	6.88 (3.27)
	Self-paced	11.77 (2.50)	11.19 (3.48)
Second delayed recall	Fixed-paced	5.31 (3.27)	3.73 (2.43)
	Self-paced	8.85 (3.21)	7.85 (4.17)
Conscious rehearsal[a]	Fixed-paced	2.00 (1.41)	2.31 (1.54)
	Self-paced	2.69 (1.69)	2.12 (1.82)

Note. [a] = mean item responses on a Likert scale from 1 (not at all) to 7 (very often).

(except for one date, where 13 participants were tested in the second session). The experimenter was always in the lab and rested with the participants. The lab consisted of 4 seats for the participants, plus an extra seat for the experimenter. Each participant had a (white) partition on his right and left, which were constructed such that the end of each partition was about 20 inches longer than the table itself. Participants carried headphones except during instructions as well as first and second delayed recall. Experimental procedure was programmed using E-Prime 2.0 software (Psychology Software Tools, 2013).

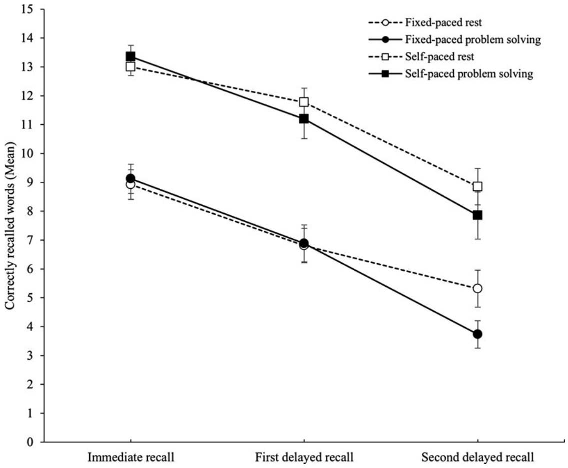

Figure 2. Mean number of correctly recalled words (max = 15 words per list) in Experiment 1 plotted separately for recall (immediate, first delayed, second delayed), study time (fixed-paced, self-paced), and post-encoding condition (rest, problem solving). Error bars represent standard errors of the mean.

Results

Data of 4 four subjects were excluded from the analysis due to missing values in the immediate recall and/or technical and motivational problems during the experiment (fixed-paced condition: $n = 26$, 23 female, mean age = 21, age range = 17–30 years; self-paced condition: $n = 26$, 19 female, mean age = 22 years, age range = 18–27 years). Data were analysed (IBM SPSS Statistics, Version 24) based on the sum of correctly recalled words. Alpha level was set at $p < .05$.

Participants studied each word on average for 7.28 sec ($SD = 3.42$) in the self-paced condition (fixed-paced condition: 1.25 sec). We conducted a mixed ANOVA with recall time (immediate, first delayed, second delayed) and post-encoding condition (rest, problem solving) as within-subject factors, and study time (fixed-paced, self-paced) as between-subjects factor. Descriptive statistics can be found in Table 1. Figure 2 shows a graphical display of the results. Results revealed that memory performance dropped significantly over time, $F(2,100) = 159.87$, $p < .001$, $\eta_p^2 = .762$. Participants in the self-paced condition showed higher mean memory performances compared to participants in the fixed-paced condition, $F(1,50) = 44.96$, $p < .001$, $\eta_p^2 = .473$. The recall time*post-encoding condition interaction was significant, $F(2,100) = 6.74$, $p = .002$, $\eta_p^2 = .119$, indicating that memory performance dropped differently in the rest and problem solving condition. The post-encoding condition*study time interaction, $F(1,50) = .001$, $p = .969$, and recall time*post-encoding condition*-study time condition interaction, $F(2,100) = 1.05$, $p = .354$, were non-significant. No other main effects and interactions were significant, $p > .1$. Simple effects analyses revealed that memory performance in the resting and problem solving condition was similar at immediate recall, $F(1,50) = .92$, $p = .321$, and first delayed recall, $F(1,50) = .30$, $p = .588$, but higher in the resting condition at the second delayed recall, after 7 days, $F(1,50) = 7.31$, $p = .009$, $\eta_p^2 = .128$. Post-hoc analyses revealed that the recall time*post-encoding condition interaction was non-significant from the immediate to the first delayed recall, $F(1,50) = 2.23$, $p = .142$, and significant from the first delayed to the second delayed recall, $F(1,50) = 4.78$, $p = .033$, $\eta_p^2 = .087$. Order-specific analyses can be found in the supplemental material.

Next, we analysed questions on participants' conscious rehearsal (Table 1). In the fixed-paced condition, 14/26 (53.85%) participants in the resting condition and 11/26 (42.31%) participants in the problem solving condition indicated that they have not rehearsed the words (score = 1). In the self-paced condition, 7/26 (26.92%) participants in the resting condition and 14/26 (53.85%) participants in the problem solving condition indicated that they have not rehearsed the words. All the other participants indicated that they have consciously rehearsed the words to some extent (score > 1). In the fixed-paced group, participants rehearsed words in the resting and problem solving condition to a similar extent, $t(25) = -.81$, $p = .425$, $d = -.159$. Spearman correlations revealed a significant negative relation between conscious rehearsal in the problem solving condition and the first delayed recall, $r = -.42$, $p = .031$, but not second delayed recall, $r = -.36$, $p = .068$. Other correlations were not significant, all p's > .2. In the self-paced group, participants consciously rehearsed words significantly more in the resting condition compared to the problem solving condition, $t(25) = 2.26$, $p = .033$, $d = .443$. Spearman correlations revealed no significant relations between rehearsal in the resting and problem solving condition and memory performance in first and second delayed recall, all p's > .2. Participants in both study time conditions (fixed-paced: $M = 15.77$, $SD = 3.68$; self-paced: $M = 15.12$, $SD = 3.90$) showed similar problem solving performances, $t(50) = .62$, $p = .537$, $d = .172$. Spearman correlations showed no significant relations between mean study time in the self-paced condition and first and second delayed recall performance in both post-encoding conditions, p's > .1.

To sum up, our central results, memory performance benefited from a brief period of wakeful rest after encoding compared to problem solving. This benefit was significant after 7 days only. Participants in the self-paced condition outperformed those in the fixed-paced condition. The beneficial effect of resting was not modulated by study time.

Experiment 2

In Experiment 2, we aimed at testing whether the found higher memory performance after 7 days in the resting condition in Experiment 1 was independent of the first delayed recall at the end of the first experimental session. Strong evidence exists that retrieval of previously learned information supports memory retention (Roediger & Butler, 2011), and that this supportive effect persists over long delays (Roediger & Karpicke, 2006a, 2006b). Results of a study from Dewar et al. (2012) with healthy elderly adults indicate that an intermediary recall between immediate and 7 day recall should not affect the resting effect. They found higher memory performances in a 10-min post-encoding resting condition compared to a 10-min spot-the-difference task condition in a delayed recall test at the end of the first experimental session and again 7 days later in a second experimental session. A second experiment, which was implemented to test the findings of the first experiment, found higher delayed memory performances after 7 days in the resting condition, even when the intermediary recall was omitted. Based on the findings of Experiment 1 and of the study by Dewar et al. (2012), we hypothesised to find (i) a higher memory performance in the self-paced than in the fixed-paced group, and (ii) a higher delayed memory performance in the post-encoding rest compared to the post-encoding problem solving condition, independent of study time.

Method

Participants

Fifty-three students (33 female, mean age = 22 years, age range = 18–37 years) took part in the experiment in exchange for course credit. Participants were randomly assigned to one of two study time conditions (fixed-paced, self-paced).

Materials and procedure

Experiment 2 was identical to Experiment 1, except that participants were required to recall the encoded words only twice, immediately after word list presentation and after 7 days (Figure 1). We conducted a mixed factors design with recall time (immediate, delayed) and post-encoding condition (resting, problem solving) as within-subject factors and study time (fixed-paced, self-paced) as between-subjects factor.

Results

Data of 3 subjects were excluded from the analysis due to missing values or technical and motivational problems during the experiment (fixed-paced condition: $n = 25$, 13 female, mean age = 22 years, age range = 18–32 years; self-paced condition: $n = 25$, 17 female, mean age = 22 years, age range = 18–37 years). Data were analysed (IBM SPSS Statistics, Version 24) based on the sum of correctly recalled words. Alpha level was set at $p < .05$.

Participants studied each word on average for 7.42 sec ($SD = 3.47$) in the self-paced condition (fixed-paced condition: 1.25 sec). We conducted a mixed ANOVA with recall time (immediate, delayed) and post-encoding condition (resting, problem solving) as within-subject factors, and study time (fixed-paced, self-paced) as between-subjects factor. Descriptive statistics can be found in Table 2. Figure 3 shows a graphical display of the results. Memory performance dropped significantly over time, $F(1,48) = 542.76$, $p < .001$, $\eta_p^2 = .919$. Participants in the self-paced condition showed higher mean memory performances compared to participants in the fixed-paced condition,

Table 2. Descriptive statistics of the mean number of correctly recalled words and mean item responses to question on conscious rehearsal (Experiment 2).

		Post-encoding condition	
		Rest *M (SD)*	Problem solving *M (SD)*
Immediate recall	Fixed-paced	8.12 (1.97)	8.20 (2.27)
	Self-paced	12.56 (2.33)	12.88 (2.46)
Delayed recall	Fixed-paced	2.88 (2.71)	2.48 (1.98)
	Self-paced	5.56 (3.53)	5.52 (3.82)
Conscious rehearsal[a]	Fixed-paced	2.60 (1.63)	2.24 (1.30)
	Self-paced	2.28 (1.43)	2.20 (1.50)

Note. [a] = mean item responses on a Likert scale from 1 (not at all) to 7 (very often).

$F(1,48) = 40.66$, $p < .001$, $\eta_p^2 = .459$. The recall time*study time interaction was significant, $F(1,46) = 9.67$, $p = .003$, $\eta_p^2 = .174$. The post-encoding condition*study time interaction, $F(1,48) = .22$, $p = .643$, and recall time*post-encoding condition*study time condition interaction, $F(1,48) = .01$, $p = .911$, were non-significant. No other main effects and interactions were significant, $p > .1$. Simple effects analyses revealed significantly higher memory performances in the self-paced compared to the fixed-paced condition at immediate recall, $F(1,48) = 64.18$, $p < .001$, $\eta_p^2 = .572$, and delayed recall, $F(1,48) = 16.34$, $p < .001$, $\eta_p^2 = .254$ (Table 2; Figure 3). The drop in the mean memory performance from immediate to delayed recall after 7 days was higher in the self-paced compared to the fixed-paced condition. Order-specific analyses can be found in the supplemental material.

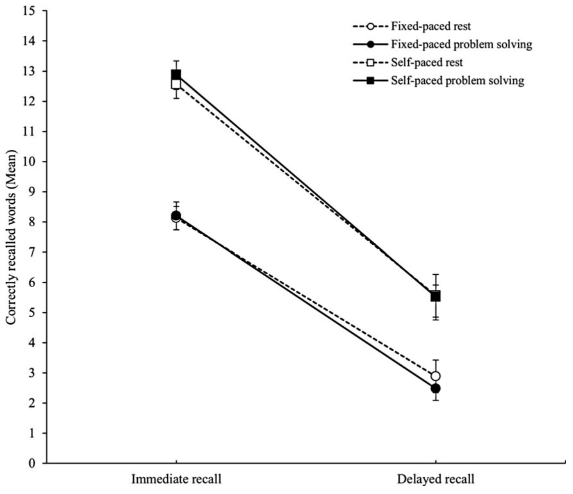

Figure 3. Mean number of correctly recalled words (max = 15 words per list) in Experiment 2 plotted separately for recall (immediate, delayed), study time (fixed-paced, self-paced), and post-encoding condition (rest, problem solving). Error bars represent standard errors of the mean.

Next, we analysed questions on participants' conscious rehearsal (Table 2). In the fixed-paced condition, 9/25 (36%) participants in the resting condition and 9/25 (36%) participants in the problem solving condition indicated that they have not rehearsed the words (score = 1). In the self-paced condition, 11/25 (44%) participants in the resting condition and 9/25 (36%) participants in the problem-solving condition indicated that they have not rehearsed the words. All the other participants indicated that they have consciously rehearsed the words to some extent (score > 1). Participants in the fixed-paced and self-paced condition showed similar rehearsal during resting, $t(48) = -.74$, $p = .465$, $d = -.209$, and problem solving, $t(48) = -.10$, $p = .920$, $d = -.028$. In the fixed-paced group, participants rehearsed words to a similar extent in the resting and problem solving condition, $t(24) = 1.14$, $p = .265$, $d = .228$. Spearman correlations showed no significant relations between rehearsal reports and 7 day memory performance in the problem solving condition, $r = .36$, $p = .084$, as well as resting condition, $r = .37$, $p = .069$. Other results were not significant, p's $> .2$. In the self-paced condition, participants rehearsed words to a similar extent in the resting and problem solving condition, $t(24) = .31$, $p = .759$, $d = .062$. Spearman correlations revealed no significant relations between conscious rehearsal in the resting and problem solving condition and memory performance in first and second delayed recall, all p's $> .2$. Participants in both study time conditions (fixed-paced: $M = 14.76$, $SD = 4.81$; self-paced: $M = 16.92$, $SD = 3.67$) showed similar problem solving performances, $t(48) = -1.79$, $p = .081$, $d = .505$. Spearman correlations showed significant positive relations between mean study time in the self-paced condition and 7 day recall performance in the rest condition ($r = .76$, $p < .001$) and problem solving condition ($r = .47$, $p = .017$).

To sum up our central results, we found no differences in memory performance over 7 days in the resting and problem solving condition in both study time conditions. Participants in the self-paced condition outperformed those in the fixed-paced condition.

Analyses of experiment 1 and 2

To analyse whether an additional (first delayed) recall in Experiment 1 affected the 7 day memory performance, we merged the data from Experiment 1 and 2 and conducted a mixed ANOVA with recall time (immediate, 7 days) and post-encoding condition (resting, problem solving) as within-subject factors, and experiment (Experiment 1, Experiment 2) and study time (fixed-paced, self-paced) as between-subjects factors. Data were analysed based on the sum of correctly recalled words. Based on the results of Experiment 1 and 2 we hypothesised that (i) self-paced learners show higher immediate and 7 day recall performances and (ii) an intermediary recall (first delayed recall in Experiment 1) modulates the resting effect after 7 days. Results revealed a significant main effect of recall time, $F(1,98) = 694.59$, $p < .001$, $\eta_p^2 = .877$, and experiment, $F(1,98) = 12.60$, $p = .001$, $\eta_p^2 = .114$, with a higher mean overall memory performance in Experiment 1 compared to Experiment 2 (Tables 1 and 2). The main effect of study time was significant, $F(1,98) = 84.18$, $p < .001$, $\eta_p^2 = .462$, with a higher overall mean memory performance in the self-paced condition compared to the fixed-paced condition. The recall time*experiment interaction was significant, $F(1,98) = 15.96$, $p < .001$, $\eta_p^2 = .140$. Simple effects analyses revealed that experiments did not differ at immediate recall, $F(1,98) = 2.75$, $p = .100$, $\eta_p^2 = .027$, but 7 day recall, $F(1,98) = 19.08$, $p < .001$, $\eta_p^2 = .163$, with a higher memory performance in Experiment 1 compared to Experiment 2. The recall time*study time interaction was significant, $F(1,98) = 5.90$, $p = .017$, $\eta_p^2 = .057$, indicating that memory retention dropped to a greater extend in the self-paced compared to the fixed-paced condition. No other main effects and interactions were significant, $p > .1$. Simple effects analyses revealed that study time condition differed significantly at immediate recall, $F(1,98) = 121.40$, $p < .001$, $\eta_p^2 = .553$, and delayed recall, $F(1,98) = 39.52$, $p < .001$, $\eta_p^2 = .287$. The recall time*post-encoding condition interaction was significant, $F(1,98) = 7.85$, $p = .006$, $\eta_p^2 = .074$. Simple effects analyses revealed that the two post-encoding conditions did not differ at immediate recall, $F(1,98) = 1.34$, $p = .249$, but 7 day recall, $F(1,98) = 4.63$, $p = .034$, $\eta_p^2 = .045$, with a higher memory performance in rest condition compared to the problem solving condition. Other results were not significant, $p's > .1$.

Participants from Experiment 1 and 2 neither differed regarding their responses on the questions whether they consciously rehearsed the words during the rest and problem solving condition nor regarding problem solving performances as well as mean self-paced inter item interval; all $p's \geq .1$. Spearman correlations showed significant positive relations between mean study time in the self-paced condition and 7 day recall performance in the rest condition ($r = .46$, $p = .001$) and problem solving condition ($r = .31$, $p = .026$).

These results indicate that 7 day memory performance was higher when information was additionally recalled at the end of the experimental session in Experiment 1.

Discussion

The present study investigated the modulating effects of study time (fixed-paced versus self-paced) and post-encoding interventions (resting versus problem solving) on delayed memory performance. Results showed that (i) participants in the self-paced condition outperformed those in the fixed-paced condition, (ii) study time did not affect the impact of the post-encoding conditions in both experiments, (iii) higher memory performances in the resting compared to the problem solving condition were only found with an additional recall, and (iv) an additional recall supported memory retention over 7 days independent of study time.

Higher memory performances under a self-paced compared to relatively short fixed-paced study time condition support existing findings that an increase in study time up to a certain point leads to higher memory performances (de Jonge et al., 2012; Unsworth, 2016; Zeelenberg et al., 2015). Explanations for the memory enhancing effect in self-paced learning can be seen in an increased amount of time an item can spent in the focus of attention (Braun & Rubin, 1998; Cowan et al., 2005), the use of metacognitive strategies (e.g. monitoring, appropriate choices and implementation of effective study strategies; Tullis & Benjamin, 2011), and encoding control strategies such as rote rehearsal, visualisation, and creating stories (Delaney & Knowles, 2005). However, it is also conceivable that time pressure under the fixed-paced condition led to higher levels of stress resulting in lower memory performance compared to the self-paced condition (Schwabe & Wolf, 2010). Study time did not modulate the impact of the post-encoding intervention, i.e. we found similar delayed recall performances in the resting and problem solving condition in Experiment 1 (first delayed recall) and Experiment 2. These findings supported our assumption that under the self-paced study time condition the post-encoding interventions should result in similar delayed recall performances. This indicates that more stable memory representations, probably through the application of different cognitive strategies to encode the to-be-remembered information, are less prone to post-encoding interference (Robertson, 2012). Contrary to our assumption, we did not find a resting effect in the fixed-paced condition and consequently no modulation effect through study time. The lack of a resting effect contradicts the majority of previous studies, which found a beneficial effect of resting by using different post-encoding tasks (Brokaw et al., 2016; Craig, Della Sala, Dewar, & Bolhuis, 2014; Craig et al., 2015; Dewar, Alber, et al., 2012; Dewar et al., 2007; Mercer, 2015). Dewar et al. (2007) assumed that any mentally effortful task that withdraws mental resources away from memory consolidation – irrespective of its content – has a detrimental effect on delayed memory performance. Based on this view, we should have found a resting effect by the application of a mentally effortful problem solving task (Raven et al., 1998) aiming at measuring abstract logical thinking. However, recent evidence exists that resting after learning does not always lead to higher delayed memory performances compared to a cognitive task delay period (Martini et al., 2017; Varma et al., 2017). In several experiments, Varma et al. (2017) varied encoding material (picture-word associations, words, faces) as well as post-encoding content and its complexity with n-back tasks. The authors found no beneficial effect of resting assuming that cognitive engagement after encoding does not interfere with memory consolidation when semantic and hippocampus-dependent episodic memory processing is only minimally involved. Similarly, Martini et al. (2017) found no resting effect in young adults by using two stories written in participants' second language as encoding material. After story encoding, participants either rested or performed a visual or verbal task, respectively. Results showed no significant differences in the number of correctly recalled story details between the two post-encoding conditions after 7 days. The authors suggested that post-encoding tasks, though mentally effortful, do not necessarily impact on delayed memory performance (compared to resting), as long as memory strength of the encoded material is high. As evidence exists that information similar to existing knowledge is often better remembered than unfamiliar information (Ericsson & Kintsch, 1995), more stable memory representations should result in similar delayed memory performances independent of the post-encoding condition. Participants in the present study were required to learn simple mono- and bi-syllabic, semantically unrelated, familiar, and easily visualisable nouns (e.g. "bird", "arm", "window"). We assume that such words, which can be associated with existing schemas, are more resistant against post-encoding interference resulting in similar delayed memory performances independent of the post-encoding condition. A direct comparison with words used as encoding material in other studies (Dewar et al., 2007; Varma et al., 2017) was hampered by the lack of detailed information on this issue. However, it has to be noted that the resting effect is observed for both common nouns (Dewar et al., 2007) and non-words (Dewar, Alber, Cowan, & Della Sala, 2014), which indicates that the resting effect appears not to be dependent on words being related to existing schemas in long-term memory.

Another explanation for our findings concerns the mental activity during the resting phase itself (Craig et al., 2014; Varma et al., 2017). Wakeful resting can be described as a state of high mental activity, during which internal thought processes (e.g. daydreaming, mind wandering, future planning) and external monitoring processes take place (Buckner, Andrews-Hanna, & Schacter, 2008). During the resting phase, such processes might increase interference with the previously encoded material resulting in similar delayed memory performances in the post-encoding resting and cognitive task delay period condition. This view is supported by findings that rich autobiographical retrieval/future imagination during resting can lower memory retention (Craig et al., 2014), which also cannot be excluded for our participants. Moreover, the presence of at least one additional person in the room (experimenter) and unexpected sounds might have led to a less restful resting phase. While some studies explicitly indicate that the experimenter left the room (Craig et al., 2015; Dewar, Alber, et al., 2012; Varma et al., 2017), it was not always clearly stated how many participants were tested together. We aimed at minimising the impact of surrounding factors (e.g. other participants, sounds) by a well-prepared testing environment. Furthermore, some studies found the resting effect even when participants were tested in groups (Mercer, 2015) and EEG was recorded (Brokaw et al., 2016). Finally, it seems that the within-group manipulation of the post-encoding condition influenced whether a resting effect occurred or not. Our analyses of a potential order effect indicate that when the resting condition was followed by the problem solving condition the resting effect was eliminated. When the resting condition followed the problem solving condition the resting effect emerged. These findings indicate that a resting effect may be eliminated due to substantial retroactive interference following a resting period. Probably the length and/or the position of the resting phase in a learning sequence is of relevance here. Most interestingly, we found evidence that an additional recall moderated the effect of post-encoding resting over the long term. We found a resting effect after 7 days (second delayed recall), but only when an additional recall took place at the end of the first experimental session (first delayed recall in Experiment 1). Only a few studies exist investigating the impact of resting by applying two delayed recall tests (Alber et al., 2014; Craig et al., 2015; Dewar, Alber, et al., 2012; Dewar et al., 2014). These studies testing healthy younger and elderly adults and amnesic patients found a significant interaction between delayed recall time and post-encoding condition only in amnesic patients, but not healthy adults. To our knowledge, our study is the first to investigate the impact of post-encoding resting on the retention of verbal encoding material in healthy young adults applying two delayed recall tests over a period of 7 days. Our results are in line with findings that recalled information has a better chance to get remembered than information that is “simply” studied again (called the “testing effect”; Roediger & Karpicke, 2006a; Roediger & Karpicke, 2006b). It is argued that a recall operation triggers reconsolidation processes, which lead to additional strengthening of the original encoding material. Antony, Ferreira, Norman, and Wimber (2017) assume that “ … retrieval integrates the memory with stored neocortical knowledge and differentiates it from competing memories, thereby making the memory less hippocampus dependent and more readily accessible in future” (p. 574). Our findings (and others in amnesics; Alber et al., 2014) indicate that this retrieval-based strengthening seems to depend on the previous encoding and post-encoding phase. In other words, the additional recall had a beneficial effect on the early consolidation of new labile memories. It is conceivable that words encoded in the resting and problem solving condition were differently neurally “tagged” (see Dudai et al., 2015), i.e. words learned under the resting condition received a different neural signature than words learned under the problem solving condition. After the additional recall of the word list, information encoded in the resting condition subsequently may have received a privileged way of consolidation during wake and/or sleep phases. Antony et al. (2017) proposes that a retrieval of information promotes the rapid development of neocortical memory representations without time and sleep. However, it is also conceivable that the additionally recalled information encoded in the resting condition received a privileged treatment not until later during sleep (see Dudai et al., 2015), which selectively enhanced the information for consolidation (Inostroza & Born, 2013). Hence, words encoded in the resting condition might have received greater offline processing than words learned under the problem solving condition. However, these assumptions are speculative and need further testing.

In summary, our study adds valuable insight into the impact of specific post-encoding and study time conditions on long-term memory performance. Results showed that post-encoding rest had a beneficial effect after 7 days, but only when the encoded information was additionally retrieved 10–20 minutes after initial encoding. Notably, learning self-paced always led to higher memory performances independent of the post-encoding condition.

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No potential conflict of interest was reported by the author(s).

Conflicts of interest

The authors report no conflicts of interest.

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