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Research report

Skill learning in mirror reading: how repetition determines acquisition

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Abstract

Practice makes perfect, but the role of repetitions in skill learning is not yet fully understood. For example, given a similar number of trials on a given task, it is debated whether repeating and non-repeating items are learned by the same neural process. When one is given training with both types of items—does one learn two separate skills, or only one? Here we show, using a mirror reading task, that practice trials with trial-unique words, and practice trials with repeated words, count towards learning to a different degree. There was no interaction between the time-course of learning repeated and unique words even within the same individuals given mixed training. While repeated words were learned faster than unique words, the repetitions-dependent gains diminished with training beyond a small number of repetitions. Moreover, the gains in performance could not be accounted for solely by the number of repetitions, as assumed by power-law models of learning; rather, the passage of time was a critical factor. Finally, our results suggest that although both repeated and new words were learned by both declarative and procedural memory mechanisms, even a single repetition of specific words could lead to the establishment of a selective differential representation in memory. The results are compatible with the notion of a repetition-sensitive process, triggered by specific repeating events. This 'repetition counter' may be a critical trigger for the effective formation of procedural as well as some type of declarative memory.

Theme: Neural basis of behavior

Topic: Learning and memory: systems and functions

Keywords: Procedural learning; Skill acquisition; Repetition priming; Power function; Declarative knowledge

1. Introduction

While there is ample evidence that repetition profoundly affects performance, it is not clear what constitutes a repeated experience to count towards gains in performance. Here we investigate the different contributions of two aspects of repeated experience to learning. The first is the similarity of experience across successive events, i.e. the repeating content of the experience. The second is repetition in the sense of the number of experienced events, i.e. the amount of practice events—often considered the major factor that affects the course of learning. For example, assuming that strings 'abac', 'caab' and 'baca' are lexical items (words) in a given language, it is not clear whether learning to read the mirror reversed forms of these words would benefit equally from training on 'abac' then 'abac' (again) as compared to 'abac' then 'caab' and how effective would one be in reading 'baca' following each of these training experiences. Given that the system accounts for words as the relevant units of experience, only the former may count as a repeated experience; if however, letters are relevant units (or alternatively single syllables or other word subunits), the latter unit may be as effectively counted as a repeated experience. From a different perspective, it is not clear whether training with both repeating items and novel items results in either of two possible extreme outcomes: two independent learning processes, or a single learning process that relates to one or more putative common aspects of the combined experience.

Practice on a given task that results in what is often referred to as skill learning, was suggested to be different from repeated experience with a given, specific, item often referred to as 'repetition priming' [15,36,40]. A current

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view suggests that repetition priming and skill learning are subserved by different memory processes (differential learning for item versus task repetition) [30,40,25]. Others, however, consider repetition priming and skill learning as related phenomena of a common memory process [28,3,49,36,16]. Hauptmann and Karni [16] have recently argued for the notion that repetition priming reflects the tuning of existing processing routines to a repeating event and that skill learning is triggered only after optimal tuning is reached, i.e. following the saturation of repetition priming effects within a given session (after a critical amount of repetitions). The difficulty in relating to skill and repetition priming as distinct or similar processes, arises, in part, from differences in the terminology [15]. For example, there is some ambiguity as to the application of the term repetition priming in cases wherein one examines repetition effects that are not limited to how a single exposure affects (one other instance of) subsequent performance with a stimulus, but rather, when multiple repetitions are afforded. Some authors [40,25] referred to repetition priming as the difference between performance on new items and performance on repeated items, while others refer to the gains in performance on repeated items compared to the initial performance with these items [29]. The latter was termed by Gupta and Cohen [15] the 'benefit of repetition' in an attempt to disambiguate the differences in terminology and working definitions.

In any training event, and clearly within the context of experiments with word lists, some important aspects of the experience are repeated in the training procedure. Thus, it is plausible to assume [9] that in every training step some aspects of the experience may be counted as a repetition of a previous event to which the system can adapt. Indeed, Masson [31] has shown that training to read mirror-transformed words containing only part of the alphabet can result in significantly larger gains in reading new words composed of the trained letters compared to new words composed of the remainder of the alphabet (untrained letters) (see also Refs. [26,27]). Nevertheless, others found no such letter specificity and argued that this implicates the level of words (semantic or otherwise) as defining the target items [19]. We posit that the repeated presentation of the same words can be considered as events having a higher degree of similarity than the presentation of new words in each trial, although the letters, in both cases, may have the same degree of similarity. From this perspective, practice with repeated words or repeating the task with trial-unique words may constitute two levels in the consistency of repetition.

A second sense of the term repetition, which can be applied to both new and repeated items encountered in a training session, refers to the number of trials as a synonym for the amount of practice. Practice-related gains in performance follow a non-linear function with respect to the number of task repetitions, i.e. improvement is rapid at first but decreases as the training progresses. One influential model, relates response times to the number of practice trials as a power function [43,4,32,1,28]. In such a function the number of repetitions is stated explicitly as the major, often only, parameter that affects the course of learning in any schedule of practice. Newell and Rosenbloom [32] consider the issue of the relationship between the time continuity in practice and the number of trials, proposing that: 'a power law in terms of time is a power law in terms of trials'. However, recent studies suggest that time per-se may critically contribute to the performance gains acquired through a given amount of practice (number of repetitions), presumably the result of post-session, time-dependent, processes [9,16,37,23,22,24,10,45].

This study was designed to assess the different contributions of these two aspects of repetition to learning. Specifically we tested the time course of learning as reflecting the gains in reaction time (RT) accrued of repeated words vs. those accrued of repeating the task with new words, and determined the differential contribution of the number of repetitions to the two training modes. We trained different groups of participants on a mirror-reading task with either repetitions on the same stimuli (same words) or different stimuli (repetition on the task using new words) and also manipulated, across groups, the amount of practice, i.e. the number of repetitions, within the same schedule of training. Such a design in which the training conditions differed across groups of subjects was adopted to ensure that the interaction between the two aspects of repetition is minimized. To further assess the interaction between repeated and new words learning, an additional group was trained in the exact design as the other groups but given both repeated and new words in a mixed fashion during training. All participants were tested for recognition of specific words used in the experiment as a measure of their declarative knowledge for these words.

Our results show that learning repeated words is independent of learning new words. Although both can be well fitted by power functions, with the number of task repetitions as the only variable, time was also a critical factor. The number of repetitions of any specific word during training played an important role in determining the time-course of learning; even a single repetition within a session was found to make a difference in performance. However, beyond a certain number of repetitions, within a given session, more repetitions of either a specific word or new words did not result in any additional performance gains.

2. Methods

2.1. Participants

Sixty-two native Hebrew speakers (age range 18–35; 29 males, 33 females) participated in the experiments. Informed consent was obtained prior to the subjects participating in the experiment.

2.2. Stimuli and task

A total of 600 Hebrew words, each four or five letters long, were used as the target stimuli. All of these words were rated, unambiguously, as either concrete or abstract in preliminary testing on a different group of young adult native Hebrew speaking individuals ($n=50$). The target words were assigned to 25 lists of 24 words each, balanced in respect to concreteness value, number of syllables and number of letters. Twelve additional lists, 24 words each, were used in the training of group 'unq*2'.

Stimuli were presented as horizontally mirror-transformed on a 17″ 60-Hz PC computer screen, subtending 2° visual angle, from a viewing distance of 60 cm. The participant initiated each trial using a designated mouse button on a standard three buttons mouse. In each trial, a fixation circle at the center of the screen was switched off and the target word appeared and remained on-screen until the subject responded. Participants were required to decide whether the target word was abstract or concrete (two-alternative forced choice) and responded by clicking one of two response buttons. Stimulus presentation and subjects' responses were controlled and recorded by a psychophysical software package running on the Linux operating system ('Psy' 1998, Y. Bonneh). Both RTs (in ms resolution) and accuracy of responses were recorded.

2.3. Design

Participants were trained in three consecutive daily sessions, about 24 h apart. A transfer test followed the last session but is not referred to in the current article [33]. In a single block, pre-test phase, participants were required to indicate the concreteness of all 600 target word presented in normal orientation using the same trial parameters as described above. This phase of the experiment served as pre-training in the concreteness judgment task prior to the mirror reading training and ensured that subjects could perform the semantic decision component of the task at near perfect level.

As demonstrated in Fig. 1a, each training session began and ended with a 'test block', and 'training blocks' were given in-between. In the test blocks 24 repeated (throughout the experiment) and 24 non-repeated (new) target words were presented in a random interleaved order. Training blocks were composed of 24 mirror transformed target words and were either composed of repeated target words (presented in a different order in each block), or new target words (presented only once during the course of the experiment). The repeated words in training blocks were the same words repeated in the test blocks. A 40–90-s rest interval was given between successive training blocks. To minimize specific word list effects, seven lists of 24 target items each, were used in the test blocks and counterbalanced across training conditions. Thus, three list orders were used and the same proportion of subjects in any experimental condition was assigned to each list order.

The groups differed with respect to the training blocks given within each session. Fig. 1b depicts the five groups to which participants were randomly assigned. Two parameters were changed across the five groups: the number of training blocks (four or eight), and whether the target words were repeated or new. Groups 'rep' ($n=9$) and 'rep*2' ($n=9$) were given training on repeated words, four and eight training blocks, respectively. Groups 'unq' ($n=12$) and 'unq*2' ($n=12$) were given training on new words, four and eight training blocks, respectively. Group 'rep+unq' ($n=6$) was given four blocks of repeated words and four blocks of new words in an alternating order.

Groups 'pr' and '2r' (Fig. 1c) received training blocks on lists of words such that each list was repeated once throughout training. The intra-list order of the items was varied across repeated presentations of a list. The words that were used in the training blocks were different from the words that were used in the test blocks. A total of 12 lists, of 24 target words each, were used in the training blocks, with eight training blocks given in each of the three training sessions (Fig. 1c). Group 'pr' ($n=7$) was given training with immediate repetition of the words in successive training blocks, while group '2r' ($n=7$) was given training with the repeated exposure to any given training block delayed by intervening the other 11 blocks.

Two recognition memory tests, Test2 and Test3, were administrated prior to the beginning of session 2 and session 3, respectively. These were paper-and-pencil recognition tests each comprising 48 words in normal orientation. Twenty four words were previously seen: of these eight words were taken from the repeated items in the test blocks (R), and two sets of eight words each were taken from the new words that were presented once in the two test blocks (at the beginning—N1, and at the end—N2) of the session. The remaining 24 words were previously unseen in the course of the experiment (U). Subjects were instructed to mark all the words that were presented in a mirror-transformed mode in the experiment.

2.4. Performance measures

Accuracy and RT were measured for both test and training blocks. Performance on the repeated and on the new words of the test blocks was considered separately in the analyses. Also, the performance in the test blocks was analyzed separately from the performance in the training blocks because, in the former, interference effects between the repeated and new words could not be ruled out. Statistical analysis was done with the general linear model (GLM) on two measures: accuracy, and RT (significance levels of 0.05, Greenhouse–Geisser (G–G) correction for non-sphericity). The independent and dependent variables are stated for each model, and a covariate was introduced to account for initial differences in baseline performance

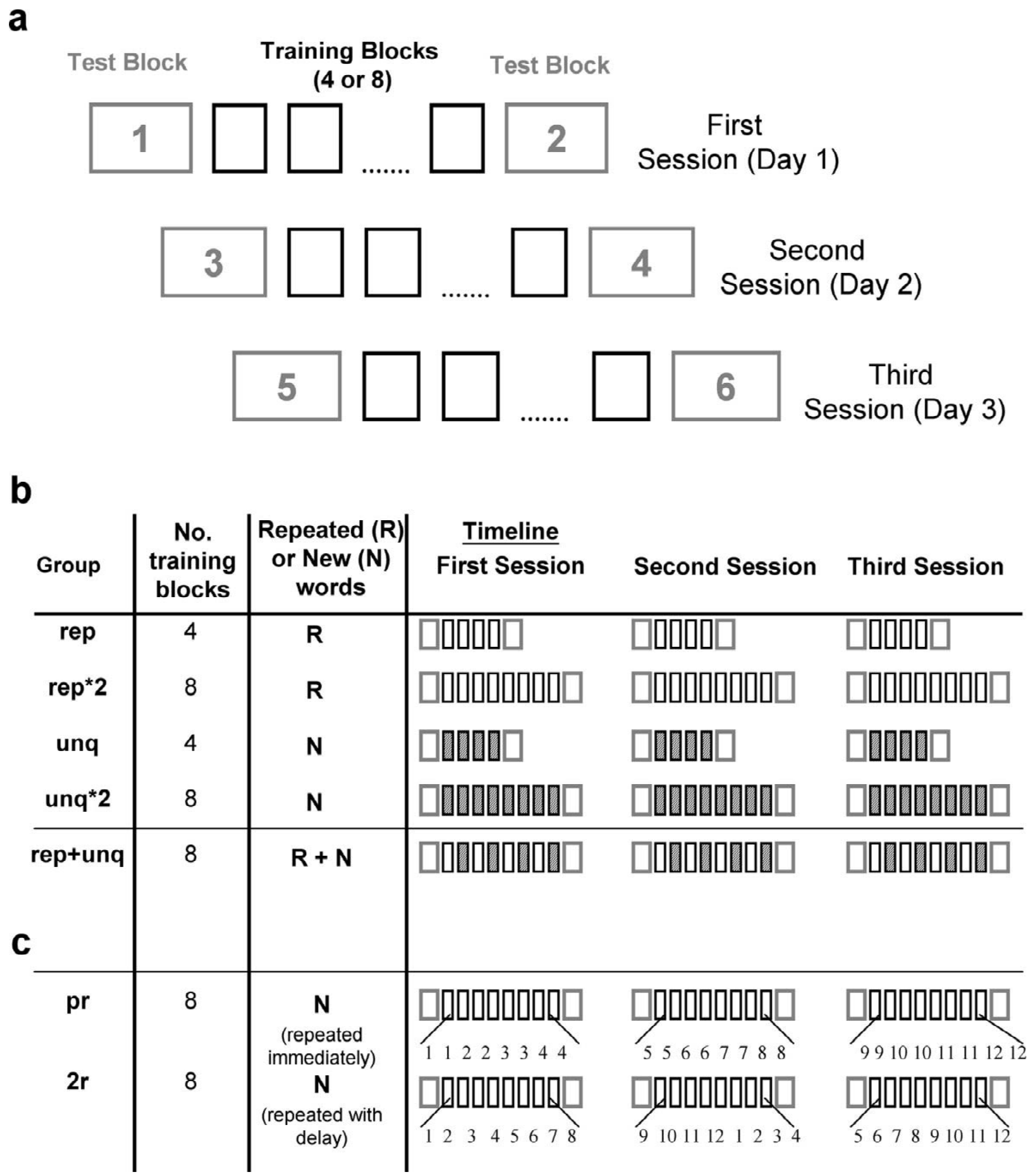

Fig. 1. The experimental design. (a) Three daily consecutive sessions. Each session consisted of an initial test block, followed by either four or eight training blocks and a final test block. A box represents a block of trials: gray boxes=test blocks, black boxes=training blocks. (b) Design for five experimental groups. Training on: repeated words ('rep', 'rep*2'); new words ('unq', 'unq*2'); and combined repeated and new words ('rep+unq'). Training blocks: open boxes=repeated words, diagonally striped boxes=new words. (c) Design for groups 'pr' and '2r'. Training blocks numbers (1–12) represent the different lists that were presented in the block.

when needed.[1] Normalized RTs were calculated per subject: the average RT in a given block was taken as a percent of the average RT in the first test block.

Power functions were fitted to the average group raw RT data using log transformation of the RT in ms and the log transformation of the block number or repetition number to obtain a linear regression function. The slopes of these regression lines, designating the rate of improvement in performance, were compared using a *t*-test (two-tailed, $P<0.05$).

The number of words marked in the recognition tests (four categories: R, N1, N2, U; see Section 2.3 above for details) were used for statistical analysis of the recognition

[1]Covariates were introduced, unless otherwise mentioned, in the following fashion: (a) for analyses of test block's RT with repeated words, the covariate was the individual subject's RT on the (to-be) repeated words in the first test block, (b) for analyses of test block's RT with new words, the covariate was the individual subject's RT on the new words in the first test block, and (c) for analyses of training block's RT, the covariate was the mean individual subject's RT on both the (to-be) repeated and the new words in the first test block. The covariates match exactly the 'first test block performance' used in the normalization procedure.

test scores (GLM, significance levels of 0.05, G–G correction).

3. Results

Participants made very few errors in categorizing the normally oriented target words in the pre-test phase. The accuracy percentage across all subjects was 97.4±3.7 and 96.5±8.1% in the initial 24 and final 24 out of the total 600 target words, correspondingly (mean±S.D.); with RTs decreasing from 1192±58 to 941±30 ms (mean±S.D.).

Participants in all groups made very few errors in categorizing mirror-transformed target words throughout training; accuracy in the test blocks was 97.2±2.5, 97.6±2.1, and 97.9±1.7% in the three sessions, respectively (mean±S.D.). Testing the differences between groups (repeated measures model with Group: all seven groups, Session: three sessions and the mean accuracy in the test blocks per subject per session as the dependent variable) revealed no significant main effects for Group, for Session, and no significant interaction of Group and Session.

3.1. Test blocks

For groups 'rep', 'rep*2', 'unq' and 'unq*2' robust gains in performance were found for both the repeated words ('rep': 2192±487, 948±195; 'rep*2': 1754±625, 810±120; 'unq': 2077±344, 1222±286 and 'unq*2': 1863±564, 1094±292; RTs in ms, 1st and 6th test blocks, respectively, mean±S.D.), and the new words ('rep': 2091±426, 1710±243; 'rep*2': 1651±570, 1381±415; 'unq': 2013±351, 1579±270 and 'unq*2': 1829±451, 1396±313; RTs in ms, 1st and 6th test blocks, respectively, mean±S.D.). Univariate repeated measures analyses, with first and last (6th) test blocks' RTs (in ms) as dependent measures, confirmed a significant learning effect in all four groups, for both repeated words ('rep': $F_{(1,8)}=98.7$, $P<0.001$; 'rep*2': $F_{(1,8)}=23.9$, $P=0.001$; 'unq': $F_{(1,11)}=90.1$, $P<0.001$ and 'unq*2': $F_{(1,11)}=31.0$, $P<0.001$), and new words ('rep': $F_{(1,8)}=10.7$, $P=0.011$; 'rep*2': $F_{(1,8)}=13.2$, $P=0.007$; 'unq': $F_{(1,11)}=29.5$, $P<0.001$ and 'unq*2': $F_{(1,11)}=38.1$, $P<0.001$).

As test blocks were identically constructed for all groups, we were able to directly compare the effects of the different training conditions, on the course of learning repeated and new words. A 4×5 repeated measures model [Group: the four groups: 'rep', 'rep*2', 'unq' and 'unq*2', Course: five test blocks (RT in the first test block was introduced as a covariate); RTs (ms) as the dependent measure], tested separately for repeated and new words, revealed Group effect only for the repeated words ($F_{(3,37)}=8.3$, $P<0.001$), and not for the new words ($F_{(3,37)}=1.2$, $P=0.34$). Moreover, the interaction of Group and Course was significant only for the repeated words ($F_{(12,148)}=3.6$, $P<0.001$). The adjusted mean RT for the four groups for repeated and new words are depicted in Fig. 2a and b, respectively. The group average of the individually normalized RT for the four groups for the repeated words, and the average of the individually normalized RT across the four groups for new words are presented in Fig. 2c.

Further analyses, comparing specific pairs of groups' performance on repeated words (2×5, repeated measures model: Group and Course; RTs in ms, as the dependent measure, RT in the first test block introduced as a covariate) showed that: (a) the performance of group 'rep' (four training blocks on repeated words per session) was significantly better than that of groups 'unq' and 'unq*2' ($F_{(1,18)}=14.1$, $P=0.001$; $F_{(1,18)}=5.6$, $P=0.030$, Group effect for 'rep' vs. 'unq', and 'rep' vs. 'unq*2', respectively). Also, the performance of group 'rep*2' (eight training blocks of repeated words per session) was better than that of groups 'unq' and 'unq*2 ($F_{(1,18)}=23.9$, $P<0.001$; $F_{(1,18)}=11.4$, $P=0.003$, Group effect for 'rep*2' vs. 'unq', and 'rep*2' vs. 'unq*2', respectively). That is, more training on repeated target words significantly improved RTs, without loss in accuracy, for reading mirror-transformed repeated words. (b) No significant Group effect was found between groups 'rep' and 'rep*2' performance (the covariate used in this model was the average of both repeated and new words in the first test block in order to comply with the homogeneity of slopes assumption). Thus, doubling the number of repetitions on specific words from four to eight training blocks in a given session led to no additional gains in performance with repeated words.

A model in which RTs on the repeated words and the new words were contrasted, separately, within each group, revealed a significant effect for repeated vs. new words in all groups [2×5, repeated measures model: 'rep': $F_{(1,8)}=181.2$, $P<0.001$; 'rep*2': $F_{(1,8)}=22.3$, $P=0.002$; 'unq': $F_{(1,11)}=28.3$, $P<0.001$ and 'unq*2': $F_{(1,11)}=72.9$, $P<0.001$)]. The importance of these findings is that a better performance with repeated words compared to new words was found already in groups 'unq' and 'unq*2' in which the repetition on specific words was limited to the test blocks. Thus, even a single repetition of a given set of words within a session resulted in significantly better performance compared to performance with new words.

Power function fits of the log transformation of the average RTs for the four training groups on repeated words in the test blocks are presented in Fig. 2d and e. We found a good fit of all data sets as indicated by the high r square values (0.82–0.96). In Fig. 2d, the *x*-axis is the log transformation of the accumulating number of repetitions of the repeated target words (in both test and training blocks). Similar slopes for 'unq', 'unq*2', and 'rep' groups (−0.290, −0.287 and −0.274, respectively), but a somewhat shallower slope for group 'rep*2' (−0.223) were found. This shallower slope of the fitted power function for the group that received more practice implies that the additional practice did not result in faster learning. However, significant differences between the slopes of the fitted

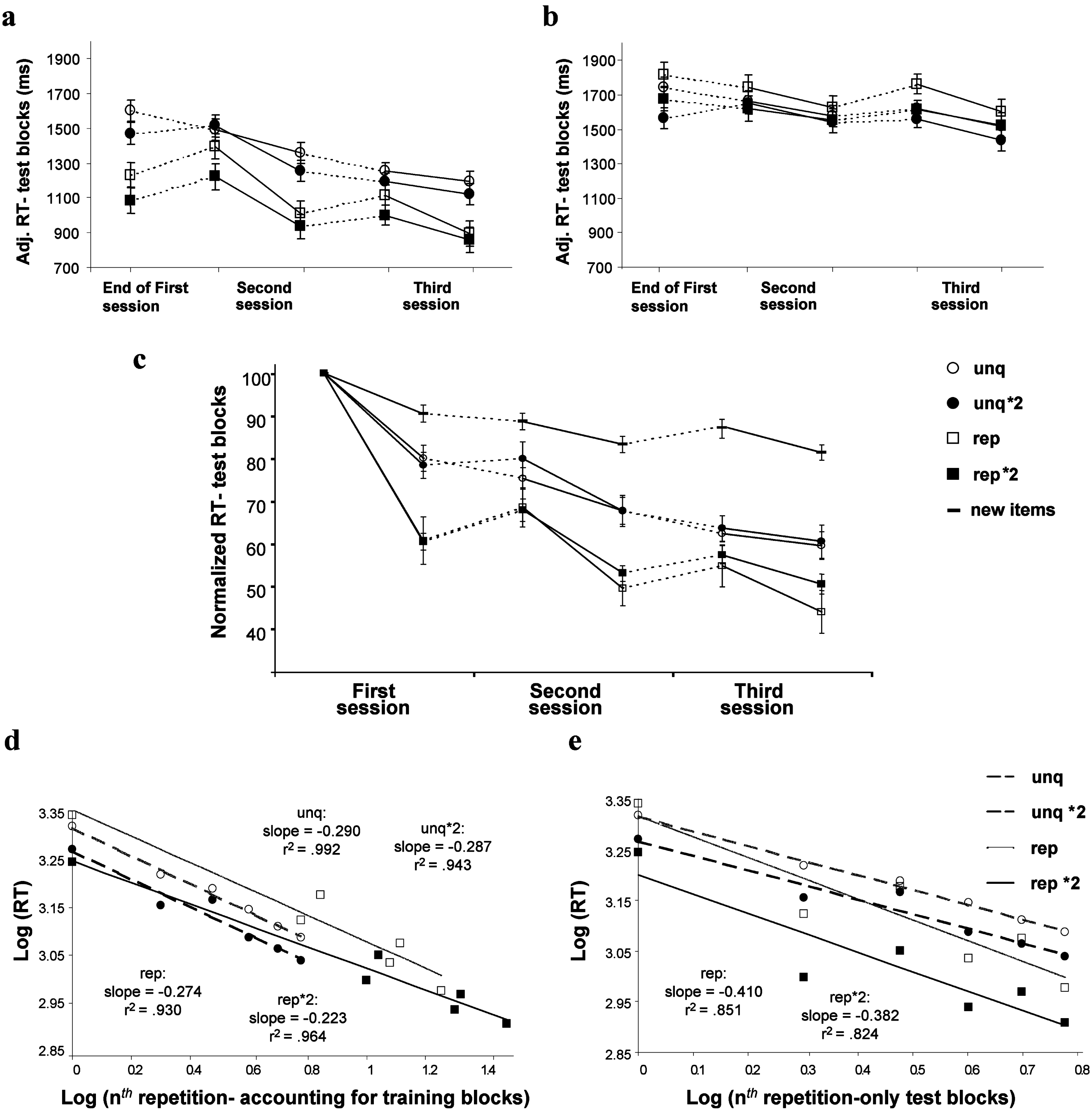

Fig. 2. Test blocks performance. Adjusted RT data for repeated (a) and for new words (b) for the four groups: open squares = 'rep'; filled squares = 'rep*2'; open circles = 'unq'; filled circles = 'unq*2'. For initial performance (RT in the 1st test block) see text. (c) Mean normalized RTs in the test blocks for repeated words (shown separately for each group), and for new words (collapsed across the four groups: dashes = new words). (d) Group averaged RTs log–log transformed data for repeated words in the four groups, as a function of the number of repetition (including the word repetitions encountered in the training blocks). (e) Group averaged RTs log–log transformed for repeated words as a function of repetition (test blocks). (d, e) Values of the power function slopes and the correlations (r^2) are presented for the different groups.

data were found only for group 'rep*2' vs. 'unq' ($t_{(8)}$ = 2.664, $P<0.05$). In Fig. 2e, the *x*-axis is the log transformation of the test block number, thus accounting for the experimental design schedule. The co-alignment of the data using time (schedule) recaptured the basic findings as described in the adjusted and normalized RT data (Fig. 2a,c), i.e. similar slopes for groups 'rep' and 'rep*2' (−0.410, −0.382, respectively) that were steeper than the slopes of groups 'unq' and 'unq*2'.

3.2. Training blocks

RTs and normalized RT of groups 'rep', 'rep*2', 'unq' and 'unq*2' in the training blocks are presented in Fig. 3a and b. Training blocks performance was better when the blocks were composed of repeated words rather than of new words, regardless of the number of training blocks in a given session [2×3×4 repeated measures model (Group: 'rep' vs. 'unq', Session, Block; RT in ms: $F_{(1,19)}=20.8$, $P<0.001$; 2×3×8 repeated measures model (Group: 'rep*2' vs. 'unq*2', Session, Block; RT in ms: $F_{(1,19)}=33.2$, $P<0.001$]. Training blocks performance was, however, indifferent to the number of training blocks given on either repeated or new words. A 2×3×4 repeated measures model [Group, Session, Block; RT (ms), RT in the first test block introduced as a covariate], revealed no Group effect for 'rep' vs. 'rep*2': ($F_{(1,15)}=1.3$, $P=0.271$) and for 'unq' vs. 'unq*2' ($F_{(1,21)}=1.6$, $P<0.219$). Thus, the across sessions retained gains of group 'rep' (four training blocks per session) were similar to those of group 'rep*2' (first four of the total eight training blocks per session). The same was found for groups 'unq' and 'unq*2', although specific list effects might have contributed to some of the fluctuations between the training blocks within each session and account for the larger variance in the results of the training blocks in the 'unq' and 'unq*2n' conditions.

To elucidate the between sessions, and the within-session effects, the RTs in the first and the last training blocks in all three sessions were compared, for the four groups [4×3×2 repeated measures model: (Group, Session, Within-session: first vs. last training blocks in a given session)]. This analysis revealed main Group ($F_{(3,38)}=17.8$, $P<0.001$), Session ($F_{(2,76)}=68.2$, $P<0.001$) and Within-session ($F_{(1,38)}=49.2$, $P<0.001$) effects, and significant interactions of the above with Group ($P<0.001$). Therefore, a similar model was tested separately for each group (3×2 repeated measures model (Session, Within-session: first vs. last training blocks in a given session)], main effects for session were found in groups 'rep' ($F_{(2,16)}=45.1$, $P<0.001$), 'rep*2' ($F_{(2,16)}=25.7$, $P=0.001$) and 'unq*2' ($F_{(2,22)}=13.9$, $P<0.001$). In group 'unq' main effect of session was found only when all four training blocks were compared (3×4 repeated measures model; $F_{(1,22)}=9.2$, $P=0.004$). Main effect for Within-session gains was, however, found only for groups 'rep' and 'rep*2' ($F_{(1,8)}=39.0$, $P<0.001$; and $F_{(1,8)}=32.5$, $P<0.001$, respectively). In addition, significant interactions of Session and Within-session effects were found only in groups 'rep' and 'rep*2' ($F_{(2,16)}=48.4$, $P<0.001$; and $F_{(2,16)}=25.8$, $P<0.001$, respectively) reflecting that the Within-session effects were higher in the initial session and decreased later on in practice.

The power function fitted to the log transformation of the averaged RTs of groups 'rep' and 'rep*2' (Fig. 3c) showed similar slopes only when the training blocks of group 'rep' were co-aligned with the corresponding training blocks of group 'rep*2' (i.e. accounting for time between sessions; rep-to-day) ($t_{(32)}=3.478$, $P<0.001$). Fitting the data set for the number of repetitions per-se (i.e. not accounting for time between sessions) resulted in significantly different slopes for 'rep' and 'rep*2' ($t_{(32)}=0.627$).

3.3. Concurrent training

An additional group of subjects, 'rep+unq' (Fig. 1b), was given concurrent training on repeated and new words. Performance gains were found for both the repeated words (1987±431, 889±177; RTs in ms, 1st and 6th test blocks, respectively, mean±S.D.) and the new words (2023±578, 1616±363; RTs in ms, 1st and 6th test blocks, respectively, mean±S.D.). Univariate repeated measures analyses (RTs in ms, 1st and 6th test blocks), confirmed a significant learning effects for both repeated words ($F_{(1,5)}=53.3$, $P=0.001$), and new words ($F_{(1,5)}=6.8$, $P=0.048$).

Fig. 4 depicts test blocks performance for group 'rep+unq' compared to groups 'rep' and 'unq'. The data is presented separately for repeated words (R-rep+unq, R-rep) and for new words (N-rep+unq, N-unq). A 2×5, repeated measures model (Group and Course; RT, in ms, RT in the first test block introduced as a covariate) revealed no differences between the performance of groups 'rep' and 'rep+unq' on the repeated words ($F_{(1,12)}<1$, $P=0.610$) and between groups 'unq' and 'rep+unq' on the new words ($F_{(1,15)}<0.1$, $P=0.891$). This remarkable similarity in performance, irrespective of the availability of concurrent training on new words, is reflected in the slopes of the respective fitted power functions for the group average RTs, which are depicted in Fig. 4c. Significant differences between the slopes for repeated words and new words were found both between groups (R-rep vs. N-unq: $t_{(8)}=5.008$, $P<0.01$) and within group (R-rep+unq vs. N-rep+unq: $t_{(8)}=9.234$, $P<0.001$).

3.4. Immediate vs. delayed repetition

Two additional groups were given one repetition on the words presented in the training blocks either in successive blocks (immediate, group 'pr') or in different sessions (delayed, group '2r') (Fig. 1b). Robust gains in performance were found in the test blocks for both the repeated words ('pr': 2176±910, 1146±342; '2r': 2043±408, 1385±336; RTs in ms, 1st and 6th test blocks, respectively, mean±S.D.), and the new words ('pr': 2061±848, 1477±349; '2r': 2150±378, 1720±323; RTs in ms, 1st and 6th test blocks, respectively, mean±S.D.). Univariate repeated measures analyses (RTs in ms, 1st and 6th test blocks), confirmed a significant learning effects for repeated words ('pr': $F_{(1,6)}=18.7$, $P=0.005$; '2r': $F_{(1,6)}=34.5$, $P=0.001$), and for new words in group '2r' ($F_{(1,6)}=54.4$, $P<0.001$), and marginally significant for new words in group 'pr' ($F_{(1,6)}=4.7$, $P=0.074$).

A 2×5, repeated measures model (Group: 'pr' and '2r', Course; RT in the test blocks, in ms, RT in the first test block introduced as a covariate) revealed main Group effect on the repeated words ($F_{(1,11)}=4.9$, $P=0.049$) but

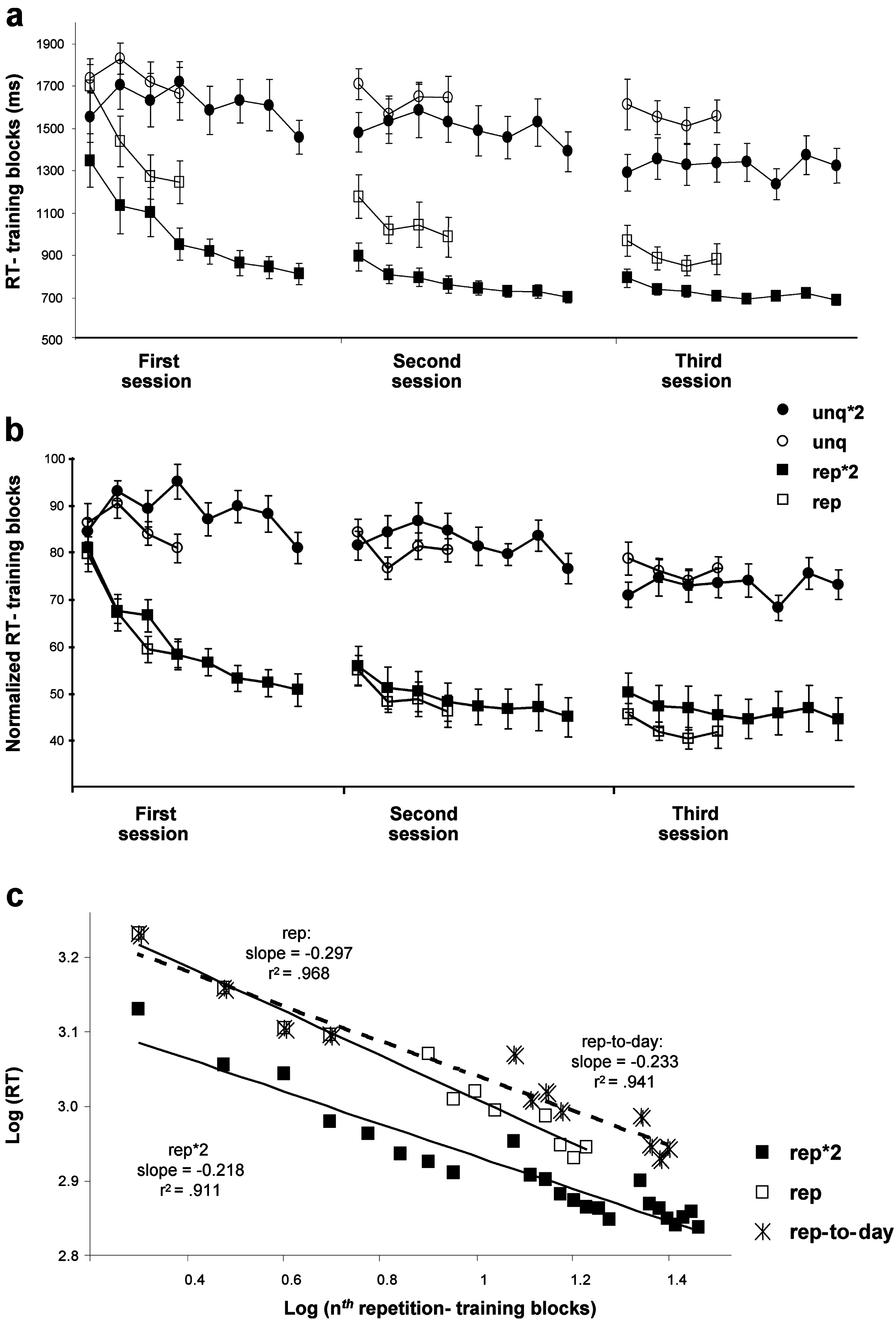

Fig. 3. Training blocks performance. Raw RT (a) and mean normalized RT data (b) for groups 'rep', 'rep*2', 'unq' and 'unq*2'. (c) Group averaged RTs log–log transformation of the data for repeated words (groups 'rep', 'rep*2') as a function of the number of repetitions. Dashed line = the regression line for the data co-aligned to time ('rep-to-day' = asterisk). Symbols and power function coefficients are shown as in Fig. 2.

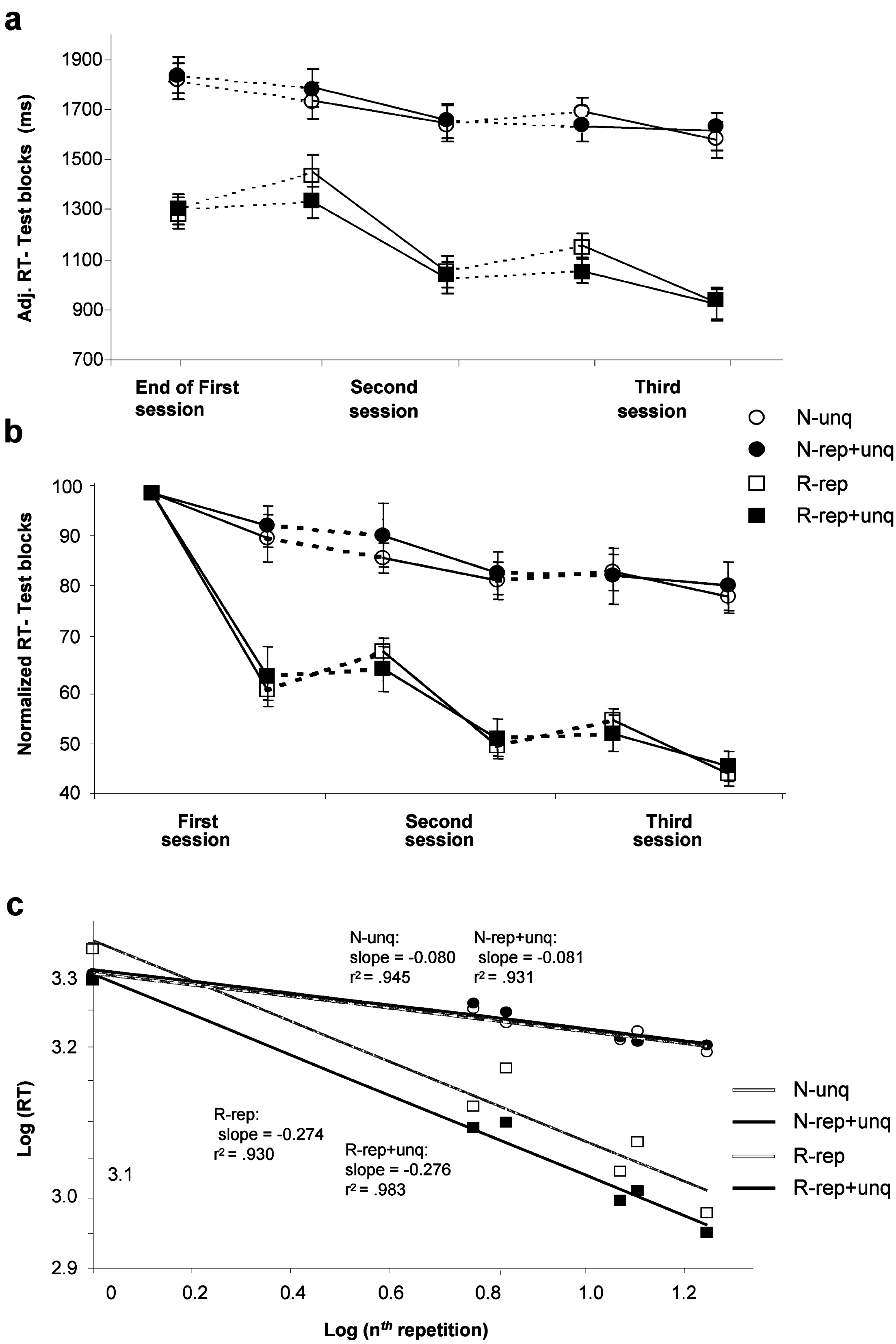

Fig. 4. Test blocks performance. (a) Adjusted RT data for repeated words [groups 'rep' (R-rep = open squares) and 'rep + unq' (R-rep + unq = filled squares)] and for new words [(groups 'unq' (N-unq = open circles) and 'rep + unq' (N-rep + unq = filled circles)]. For initial performance (RT in the 1st test block) see text. (b) Mean normalized RT corresponding to the data sets presented in a. (c) Log group averaged RTs corresponding to the data sets presented in a, plotted against the log number of repetition (on word: R-rep, R-rep + unq, or on the task: N-unq, N-rep + unq) including the trials encountered in the training blocks. Power function coefficients are shown as in Fig. 2.

not on the new words ($F_{(1,12)}=1.1$, $P=0.317$; a covariate was not introduced due to a violation of the homogeneity of slopes assumption). Thus, as can be seen in Fig. 5a the RTs of group 'pr' on repeated words in the test blocks were faster than those of group '2r'. The group average RTs, collapsed across the two groups for new words are also depicted in Fig. 5a (upper line). Fig. 5b depicts the corresponding group average normalized RTs.

The differences in performance between the groups on repeated words were also shown by a significant difference between the slopes of the power functions fitted to the average group RTs on repeated words shown in Fig. 5c ($t_{(8)}=3.238$, $P<0.02$)

3.5. Recognition tests

There were no significant differences in the recognition tests scores for doubling the amount of training both on the repeated and on the new words as indicated by analyses using a 2×4 repeated measures model with Group ('rep' vs. 'rep*2' or 'unq' vs. 'unq*2'), and Recognition test condition score (R, N1, N2, U; see Section 2.3 for details, as dependent variable). Therefore, the results of groups 'rep' and 'rep*2' and the results of groups 'unq' and 'unq*2' were pooled together, into two training conditions; groups trained on repeated words (pooled 'rep' and 'rep*2') and groups trained on new words (pooled 'unq' and 'unq*2') (Fig. 6). A 2×4 repeated measures analysis (Group: pooled 'rep' and 'rep*2' vs. pooled 'unq' and 'unq*2') revealed a significant interaction of Group and Recognition test condition score (Test2: $F_{(3,120)}=13.82$, $P<0.001$; Test3: $F_{(3,120)}=7.12$, $P<0.001$). Further hypotheses tests in this model revealed that the interaction was due to higher scores on repeated words (R) for groups trained with repeated words compared to groups trained with new words (Test2: $F_{(1,40)}=8.18$, $P=0.007$; Test3: $F_{(1,40)}=11.02$, $P=0.002$), while the opposite pattern was found for groups trained with new words wherein the scores for new words (N1) were higher [Test2: $F_{(1,40)}=10.50$, $P=0.002$; Test3 (marginally significant): $F_{(1,40)}=3.79$, $P=0.059$] with a corresponding increase in the number of filler words wrongly marked (U) (Test2: $F_{(1,40)}=8.63$, $P=0.005$; Test3: $F_{(1,40)}=5.54$, $P=0.024$). Thus, training on repeated words and new words resulted in different patterns of declarative knowledge irrespective of the amount of training.

Significant interactions of Group and Recognition test condition score were also found when the performance of group 'rep+unq' was compared to the performance of the groups trained on repeated words (Test2: $F_{(3,66)}=3.9$, $P=0.017$; Test3: $F_{(3,66)}=3.9$, $P=0.016$) (Fig. 6). Further analysis showed that the R score of the groups were not different, however, 'rep+unq' subjects were better in the N1 scores (Test2: $F_{(1,22)}=4.9$, $P=0.038$) and had a higher number of wrongly marked filler words (U) (Test2: $F_{(1,22)}=12.9$, $P=0.002$; Test3: $F_{(1,22)}=7.4$, $P=0.013$). No significant differences were found when comparing recognition test performance of group 'rep+unq' and the groups trained on new words. No significant differences in the recognition tests scores were found between groups '2r' and 'pr'.

4. Discussion

Taken together, the results of the present study show that both the nature of the repeating event and the number of repetitions determine the time course of learning. Learning to read mirror-transformed repeated words and mirror-transformed new words occurred at different rates and independently of each other. Our results also suggest that even a single repetition of a specific word may lead to the establishment of a selective differential memory. In line with recent studies of the acquisition of perceptual and motor skills [21,22], we show that accounting for the number of repetitions per-se is not sufficient to fully describe mirror reading learning, rather time is also found to play an important role in determining the course of learning, as is detailed below.

4.1. What constitutes an item repetition for learning mirror-reading?

The participants in the present experiment were asked to perform, and assessed as to their ability to carry out, a semantic decision task on single words. In such task, a word unit level of representation is critical for task performance and therefore the exposure to the same words constitutes a more consistent experience then the exposure to new words.[2] We do not, however, construe our findings as supporting the notion of a lexicon of word representations, because the results can just as well be explained by the notion that the reading system is selective for (tuned to differences in) the order of letters in letter string. Indeed, experiments that use the task of lexical decision showed that repeated mirror-transformed non-words were effectively learned (e.g. Ref. [36]). From this perspective, in the case of task repetition with new words one presumably encounters repeating events with a relatively small degree of similarity and in the case of repeated words, a large degree of similarity. Our results can, therefore, be interpreted as the contrasting effects of experience with different levels of similarity in a set of training events. Given that similarity of experience is an empirical parameter rather than an absolute theoretically derived term [3,9,35], the similarity across practice events can be accounted for in terms of what the processing system recognizes as a repeated experience and may constitute an important factor determining the systems' learning behavior [20]. In line

[2]This does not refer to the notion of levels of processing [5] since the encoding task and the retrieval mode were identical in our case.

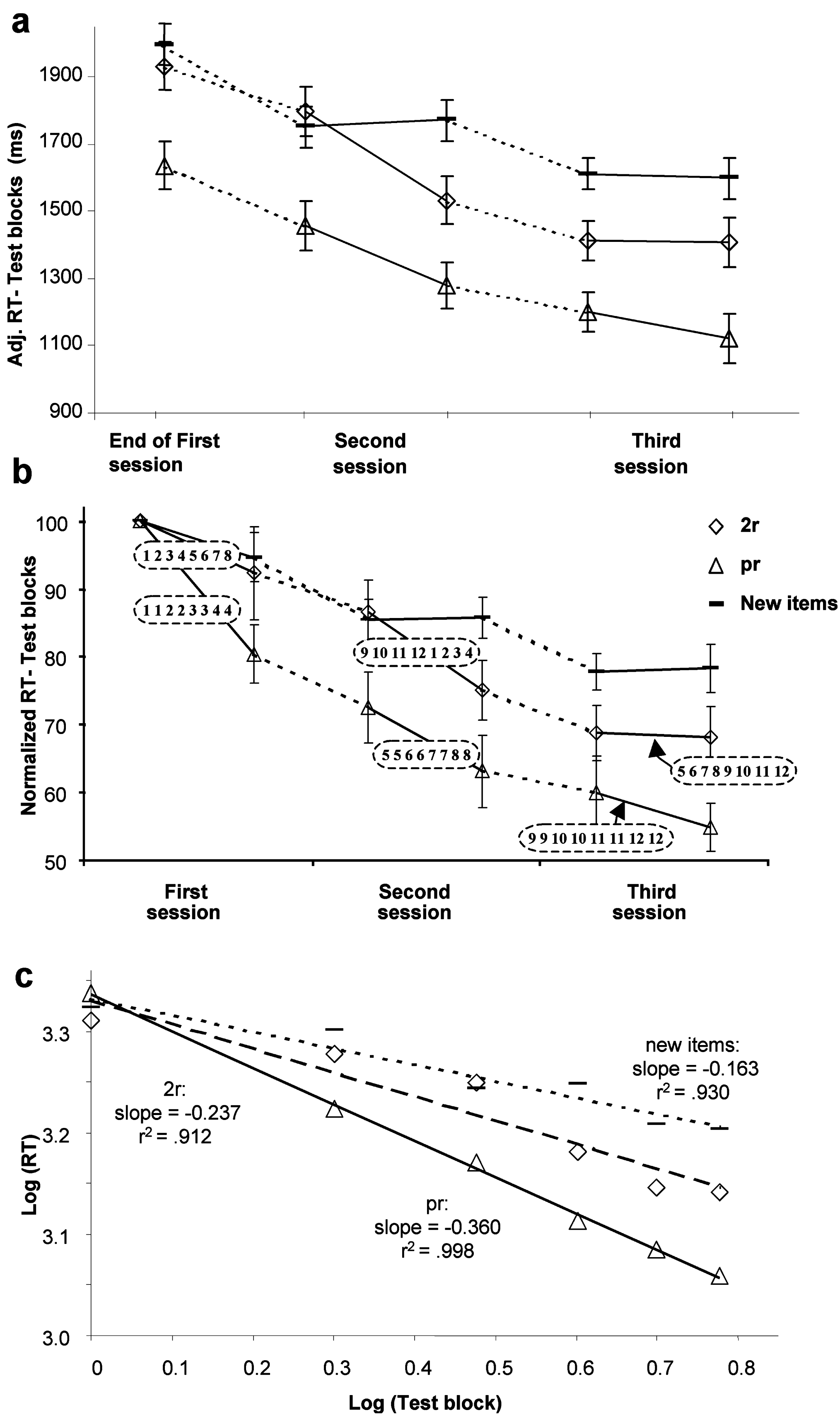

Fig. 5. Test blocks performance. (a) Adjusted RT data for groups '2r' and 'pr' for repeated words (shown separately for each group: triangles = 'pr', diamonds = '2r') and for new words (collapsed across the two groups = dashes). For initial performance (RT in the 1st test block) see text. (b) Mean normalized RT corresponding to the data sets presented in a. Insert numbers (1–12) represent the different lists that were presented in each training block. (c) Power function fit, slope and fit correlation of the log group averaged RTs corresponding to the data sets presented in a. Power function coefficients are shown as in Fig. 2.

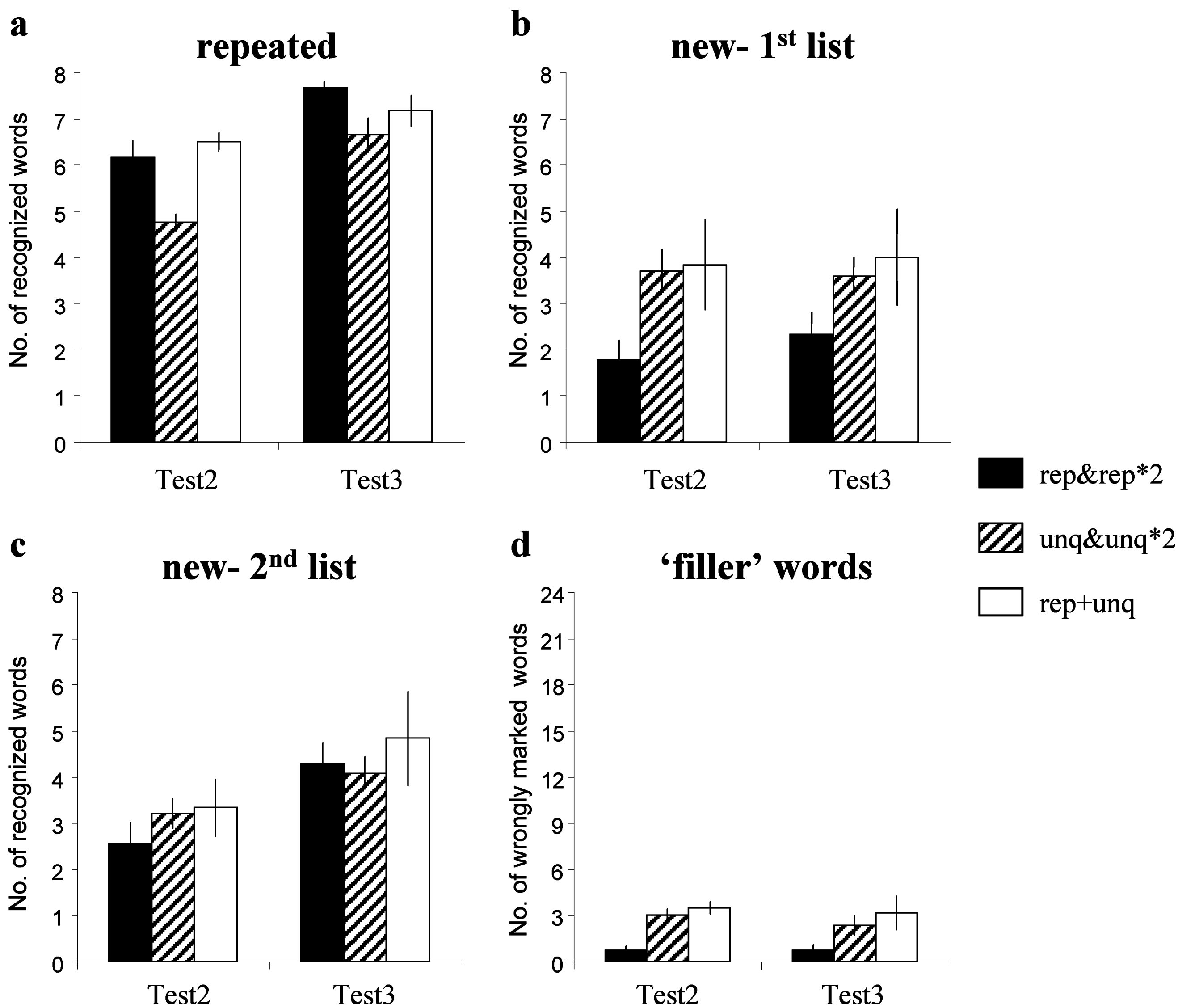

Fig. 6. Recognition tests scores. Mean number of marked words in the paper-and-pencil recognition tests (Test2 and Test3 administrated prior to session 2 and session 3, respectively). (a) Words that were repeated in the test blocks. (b, c) new words in either the first or last test blocks, respectively. (d) Wrongly marked filler words. Data for three training conditions are shown: pooled 'rep' and 'rep*2'groups (rep&rep*2) = black columns), pooled 'unq' and 'unq*2' groups (unq&unq*2) = diagonally striped columns), 'rep + unq' group = diagonally brick styled columns.

with Duncan's argument [9] our results suggest that some similarities of experience are counted as units for accumulating experience while others are not. This view goes beyond what Schneider and Shiffrin [38,42] termed as the dichotomy of 'consistent mapping'—'varied mapping' in training, by suggesting levels, or degrees, of consistency that may critically and non-linearly affect a learning system.

Our results clearly show that while a single word repetition is sufficient to trigger enhanced performance and a steeper learning curve, the recurrence of letters and even multi-letter units (syllables) in 'low-similarity' practice (new words) did not result in significant performance gains. Since the group average time course of learning both new words and repeated words were well fitted by power functions-generally accepted as indicating skill learning ([28,1,32] but see below Section 4.4)—our data are compatible with the notion that both new and repeated words were learned as [a] procedural skills. The results of the current study are in line with the notion that what Gupta and Cohen [15] term the 'benefits of repetition' come into effect whenever repetition is afforded, however the degree of similarity across repetitions may determine their magnitude.

4.2. Independent learning for repeated and new words

New words and repeated words were learned at different rates and to a large degree, independently of each other. First, the data from the test blocks (Fig. 2a–c) show that when the same overall amount of training was given, either on repeated or on new words, the gains for repeated words were larger and evolved faster. Thus, repeating the words and not merely repeating the task with new words was a critical factor for the differential gains. This was clearly shown in the results of the test block performance of group 'rep+unq' (mixed, concurrent, training): on repeated words, performance was as good as that of group 'rep' (which received but half the amount of task repetition) but was significantly better than that of group 'unq' (Fig. 4a,b).

Second, there were no differences in the test blocks gains for new words across all training conditions. Thus, under the conditions used, new words learning gains were not affected by concurrent training with different amounts of repeated words and also unaffected by the amount of training with new words. The similar, and relatively small, gains for new words across all groups may indicate that the practice afforded in the test blocks (which constituted identical training experience across all groups) was sufficient for participants to attain the maximal possible gains for new words. One cannot rule out, however, the possibility that training with a different number of new words, may lead to differential gains for new words.

Taken together, the time-course data consistently show that learning repeated and new words in all of the tested conditions did not interact: experience in one condition had no effect on the learning in the other condition irrespective of the relative amount of training given in each condition. The independence of learning repeated words from learning new words, even when both are presented to the same participants within each session, and, on the other hand, the finding that the reading of new words was similarly effective in all groups suggests the existence of a repetition sensitive process, which depends on the degree of similarity in repetition. The different time courses and the independent learning of repeated and new words need not imply the operation of distinct processes within procedural memory. The data are compatible with the notion that two separate skills can be acquired by training with new and by training with repeated words. Indeed, functional brain imaging data support the notion that learning-related changes associated with repeated and new items learning occur within the same neuronal system [36].

4.3. Effects of the amount of practice

For both new words and repeated words increasing the amount of within-session training from four to eight blocks had no significant effect on the performance at the end of the session, or in any of the subsequent sessions, suggesting that more practice (within a given session) was superfluous. However, the comparison across all groups using the test block performance, suggests a more complex pattern of the effect of the amount of practice on learning (Fig. 2). The gains from two within-session repetitions given in the test blocks ('unq' and 'unq*2' conditions) were significantly smaller than the gains from four additional training blocks of repeating words ('rep' condition). Thus, a single repetition of a short list of words was sufficient to change the course of learning compared to performance on trial-unique words. Further increasing the number of word repetitions led to higher gains in performance. However, when given training above a certain number of within-session repetitions long-term performance was unaffected though short-term within-session gains may occur (Fig. 3). Thus, our results show a complex relationship between the amount of practice and the course of learning. Moreover, the number of trials per-se, does not sufficiently account for the learning in both the repeated and new words conditions.

4.4. Effects of time

Our data provide several compelling indications for the critical role of time in the learning of both repeated and new words. First, fitting the data to a power function with respect to the time schedule of training was found to yield a better description of the learning effects compared to fitting the data to the number of repetitions per-se (Figs. 2c and 3b). Second, our results show that there were different contributions of time to the course of learning repeated words and new words. Significant within-session gains were found only for training with repeated words and not for training with new words (Fig. 3a). Third, our results show that repetition within the limited time-window of a single session resulted in better performance on a different set of repeating words, significantly more than the gains accrued when repetition was delayed by a day or two (Fig. 5).

In skill learning experiments the passage of time per-se could sometimes be confounded with the accumulation of the experience in training. The importance of time per-se for skill learning was shown in phenomena such as time-in-sleep dependent gains [24,45,10] and between-session gains [22,23,16,41] with perceptual and motor skills. In general ample evidence shows the advantageous benefits of spaced vs. massed training to learning [48,18,14]. Such time-related gains have been interpreted as reflecting consolidation processes in the neuronal system [8,20]. Furthermore, mechanistic explanations that draw upon consolidation processes have been provided to account for the superiority of spaced over massed training in animals [50]. It is noteworthy, however, that our experimental protocol goes beyond the time-frame investigated in major chapters of research on massed vs. spaced practice in human subjects, in which massed training often refers to repetitions in training on a scale of seconds [48] (or repetition with different numbers of intervening items [34]). In the present study each block was separated by at least 40 s from a succeeding block, and each word appeared just once in any given block of 24 words. In this respect, all practice given to subjects in the current study could be considered 'spaced' practice. Our data demonstrate an important contribution of time to the acquisition of a cognitive skill, specifically, for spacing practice across days, and thus, congruent with the notion of time-dependent processes of latent learning on a time scale of hours and days shown previously for perceptual and motor skills.

4.5. Repetition and different memory systems

The most parsimonious interpretation for the lack of effect of training with new words on unique words learning and vice versa is that the learning of new words and repeated words are to a large degree independent of one another. Thus, the large differences in, and the independence of, the time-courses for learning repeated and new words in our training protocol, indicate that mirror-transformed new words and repeated words were learned differently. Our results however, do not imply that two different memory systems subserve the learning of repeated and new words. Neuropsychological studies in amnesic patients, and lesion studies in animal models support the broadly accepted notion of distinction between procedural and declarative memory systems [44,3,11]. From this perspective, a memory system is defined in terms of a commonality of brain mechanisms, kind of information processed, and principles of operation [47,39]. In a landmark study, Cohen and Squire [2] found that amnesic patients can learn to read mirror-transformed words, but were worse than controls on repeated words. Nevertheless, the presumed loss of declarative memory in the amnesic patients resulted in only minor performance deficits relative to the normal controls suggesting limited contributions of declarative memory to the overall practice dependent gains [2].

In the current study the recognition test data showed that subjects trained on repeated words were better able to recognize these words by the next day compared to subjects trained on new words. Can this better 'declarative knowledge' be the only contributor to the larger gains in the mirror-reading task in these subjects? Not necessarily. Patients with Alzheimer's disease (AD), characterized by severe explicit memory deficits, were shown to have normal learning of unique and repeated mirror-transformed word triads, but were impaired in discriminating the repeated words from distractors at later recognition tests [7]. Thus, the neuropsychological evidence suggests that item-specific information may rely on repetition effects that are not directly related to explicit knowledge. In line with this notion, it was shown that amnesic patients could acquire new associations via repetitions [12,13].

The recognition test data seems to mirror our mirror-reading data, i.e. even a single within-session repetition was sufficient to improve memory for specific words; however, beyond a critical number of repetitions (six to 10) there were no additional gains. Furthermore, concurrent training on repeated and new words did not affect the recognition scores compared to the corresponding non-concurrent training conditions. Two opposing explanations may account for such a possible correlation between these two measures of memory. Either procedural knowledge leads to declarative knowledge or declarative knowledge may lead to procedural knowledge. These ideas are reflected in computational models [46,1]. We, however, wish to suggest a third possible relationship, which stresses that repetition, whenever afforded, serves as a basic facet of memory formation [37,17,6,49]. The main thrust of our argument is that the similarity between the mirror-reading RT data and the recognition scores may reflect the outcome of a basic, repetition dependent, memory process that contributes to both procedural and declarative memory systems [6,49].

5. Summary and conclusions

We show that repeated and non-repeated mirror-transformed words are learned independently of each other. We propose that given the benefits of repetition to learning and memory, a repetition sensitive process exists in multiple memory systems, which is triggered when a given degree of consistency between repeated practice trials occurs. Although this triggering is critical for procedural learning, and not essential for declarative learning, it nevertheless constitutes an effective factor for enhancing some types of declarative memory. At least one item repetition within a limited time window of a session may trigger the proposed system. Few item repetitions within a session lead this proposed system to optimal performance, as expressed in maximal gains within session. However, more than a critical amount of repetition is superfluous.

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