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Short article

The Hebb repetition effect as a laboratory analogue of novel word learning

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The present study tests the hypothesis that a common ordering mechanism underlies both short-term serial recall of verbal materials and the acquisition of novel long-term lexical representations, using the Hebb repetition effect. In the first experiment, participants recalled visually presented nonsense syllables following a typical Hebb effect learning protocol. Replicating the Hebb repetition effect, we observed improved recall for repeated sequences of syllables. In the second experiment, the same participants performed an auditory lexical decision task, which included nonwords that were constructed from the syllables used in the first experiment. We observed inhibited rejection of nonwords that were composed of the repeated Hebb sequences, compared to nonwords that were built from nonrepeated filler sequences. This suggests that a long-term phonological lexical representation developed during Hebb learning. Accordingly, the relation between immediate serial recall and word learning is made explicit by arguing that the Hebb repetition effect is a laboratory analogue of naturalistic vocabulary acquisition.

Keywords: Immediate serial recall; Novel word learning; Hebb repetition effect.

Ever since a distinction was made between short-term and long-term memory, theorists have been interested in how temporary short-term memory traces are transformed into stable long-term representations (e.g., Atkinson & Shiffrin, 1968; Burgess & Hitch, 2005). This has particularly been true for verbal short-term memory (or verbal working memory) because the transition of phonological information from short-term to long-term representations is assumed to constitute the basis for human language learning (Baddeley, Gathercole, & Papagno, 1998). Although numerous well-established theories of short-term serial recall (e.g., Burgess & Hitch, 1999; Page & Norris, 1998) on the one hand and of vocabulary acquisition on the other hand (e.g., Baddeley

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et al., 1998; Gupta, 2003) exist today, it remains unclear whether and how the mechanisms responsible for the short-term retention of verbal information interact with the learning of novel word-forms. The current study is aimed at clarifying the theoretical link between these two, probably most important, functions of verbal working memory. We argue that the learning seen in an immediate serial recall task over repeated presentations of a given list draws on the same processes as those that lead to the development of long-term phonological lexical representations.

The involvement of verbal working memory in both the immediate serial recall task and the learning of phonological word-forms has been documented in the literature in two lines of research that coexist and develop independently of each other. Indeed, several influential models of short-term memory for serial order are based on phonological working memory (e.g., Burgess & Hitch, 1999; Page & Norris, 1998), in as much as the latter is responsible for ordered recall of speech-based materials. But the phonological loop is also known to support language learning, and a good deal of theoretical, developmental, and neuropsychological work supports this position (e.g., Baddeley et al., 1998; Duyck, Szmalec, Kemps, & Vandierendonck, 2003). In addition, there is also indirect empirical support for the relation between immediate verbal serial recall (IVSR) and language learning, coming from a series of correlational studies that observed associations between verbal short-term memory task performance (e.g., immediate serial recall of words, verbal span tasks, nonword repetition) and vocabulary acquisition (e.g., Baddeley et al., 1998; Gupta, 2003). To our knowledge, no study has ever directly demonstrated, through experimental manipulations, that the processes underlying learning in IVSR (see, e.g., Burgess & Hitch, 1999; Gupta, 2003; Page & Norris, 1998, for a detailed description of this mechanism) are the same as the processes underlying the development of long-term word forms (lexical representations), as this correlational evidence suggests. This is the aim of the present study.

We investigated this proposition by using a paradigmatic example of the interface between short-term and long-term verbal memory—namely, the Hebb repetition effect. In his seminal work, Hebb (1961) asked participants to perform an IVSR task in which one particular sequence of digits was repeated every third trial. He observed that recall performance for the repeated sequences increased substantially when compared with performance of the nonrepeated sequences, a phenomenon that is known as the Hebb repetition effect. Hebb argued that encoding a sequence in short-term memory generates a long-term trace that outlives short-term memory. There has been a renewed interest in the Hebb effect during the last decade because the paradigm has proved to be useful for the validation of several (computational) models of verbal short-term memory (e.g., Burgess & Hitch, 2006; Cumming, Page, & Norris, 2003).

In essence, the Hebb repetition paradigm reflects how immediate serial recall of a repeated sequence of information involves the gradual development of a stable and durable representation of this information in long-term memory (Hebb, 1961). If short-term serial recall, which forms the basis for the Hebb effect, and word-form learning rely on the same phonological processing mechanism, the long-term representations acquired in Hebb learning should be equivalent to the long-term representations formed during the acquisition of new vocabulary. Naturally, the acquisition of new vocabulary will also eventually involve a mapping between the newly acquired sequence (i.e., the word-form) and meaning. However, in the current experimental operationalization of word learning (following the earlier working-memory literature, e.g., Baddeley et al., 1998), word learning is defined primarily as the acquisition of form representations. Mapping form to meaning is beyond the scope of this paper. Our working hypothesis is that the long-term serial-order memory component of word-form learning depends on the same mechanisms as those underlying the Hebb repetition effect. In this view, the Hebb repetition effect is a laboratory analogue of real-life word learning (development of word-form representations). Interestingly, the Hebb effect has already been adopted once in the literature that correlates verbal short-term memory performance with vocabulary acquisition. Very recently, Mosse and Jarrold (2008) showed that the magnitude of Hebb learning, both in IVSR and in spatial serial recall, correlates with performance on a separate nonword paired-associate learning task.

The idea that the long-term representations formed during verbal Hebb learning are of a phonological nature is of great interest not only to memory research but also to psycholinguistics. In that literature, there is growing consensus that phonological processing is essential and mandatory in all forms of language processing, not only in speech production and perception, which by definition rely on phonology, but also, for example, in visual word recognition by monolinguals (Frost, 1998) and bilinguals (Duyck, 2005). In his seminal work on this phonological theory, Frost (1998) argued for the nonneutrality of the core lexical representations, implying that lexical entries are primarily of a phonological nature, or "phonological entities defining meaning" (p. 75), and not, for example, of an orthographic nature. This was explained by Frost through the so-called speech-primacy axiom: "Spoken language is the base onto which written language is subsequently appended" (p. 74). Indeed, from a developmental perspective, it is clear that children acquire phonological representations before orthographic representations. So, because phonology is such an important aspect of processing and representations of language, it is plausible that it is also crucial for the acquisition of language. In this view, it is essential that the long-term representations formed during Hebb learning and the lexical representations formed during the early stages of vocabulary acquisition are of the same, phonological, nature.

If the long-term representations formed during Hebb learning are indeed functionally equivalent to lexical representations developed during vocabulary acquisition, it should be possible to demonstrate that Hebb materials enter the mental lexicon, just like novel word-forms do. Two experiments were designed in order to examine this. In the first experiment, participants were required to learn sequences of nonsense syllables following a Hebb learning protocol. In the second experiment, nonwords were constructed from the syllables presented in the first experiment, both from the nonrepeated and from the repeated (Hebb) sequences. To investigate whether these sequences were stored in the mental lexicon during Hebb learning, they were used as nonword materials in the task that is most often used in psycholinguistics to investigate lexical access—namely, lexical decision. Hence, for this second experiment, the following prediction was made: If Hebb learning implies the development of lexical representations, participants will be inhibited to reject the Hebb materials as nonwords. Therefore, the nonwords constructed from the repeated (Hebb) sequences should yield slower lexical decision times than nonwords based on the nonrepeated sequences.

EXPERIMENT 1

Method

Participants

A total of 42 first-year university students (29 female, 13 male) participated for course credits. They were all Dutch speaking and naive to the purpose of the study.

Materials

Sequences of nine nonsense syllables were presented to the participants for immediate serial recall. These syllables were all consonant–vowel structures (CVs; e.g., "fi, wa, ri, mu, . . . ") that have no meaning in the participants' native language. As most participants have English as a second language, we also discarded CVs that are words in English (e.g., "no, we, . . . "). In total, 64 CVs were used. Each participant completed two blocks of 36 sequences. Within one block, the same sequence was repeated every third trial. This means that we had 24 nonrepeated sequences (or filler sequences) and 1 sequence that was repeated 12 times (i.e., the Hebb sequence). Because the matching of the Hebb and filler sequences is of crucial importance with regard to the purpose of this study, we decided to use identically the same sequences for repetition and nonrepetition trials, counterbalanced across participants. More precisely, three different CV sequences were constructed per 3 participants. For the first participant, the first sequence was used for repeated trials, and the syllables from the remaining two sequences were used for the nonrepeated trials. For the second participant, the second sequence was repeated, and the other two sequences were used to produce filler lists. For the last participant in the threesome, the third sequence was used on repeated trials; the first two were used for the fillers. This implies that every single participant had different Hebb and filler sequences, which minimizes the risk for stimulus-specific effects.

Experiment 2 requires that nonwords are formed from the CV sequences presented in Experiment 1. For example, the sequence “lo fo du so wu jo le ki vi” would yield the nonwords “lofodu”, “sowujo”, and “lekivi”. We kept only the order of the CVs within these virtual nonwords constant, not the order of the nonwords within the entire sequence. For example, a possible Hebb repetition of the sequence above would be “*so wu jo le ki vi lo fo du*”. This is a more conservative approach than a typical Hebb procedure, in which all nine CVs would be presented in the same order at each repetition trial. Because using partial repetitions is likely to counteract Hebb learning and thus should work against our hypothesis, this adds strength to any Hebb effect yielded by this procedure.

The filler sequences were constructed as follows. As we explained before, we used three different CV sequences per participant, one for Hebb repetition and two filler sequences. Since 24 filler sequences are required per block, they were constructed out of the initial two sequences, by changing the order of the constituting CVs. This means that per block, filler sequences consisted of the same CVs, but with the CVs presented in a different order. This way, the CVs in the filler sequences were presented an equal number of times as the CVs in the repeated (Hebb) sequences, so that any differences in processing repeated and filler materials in Experiment 2 could by definition not be confounded by larger familiarity with the CVs in the Hebb sequences. Because out of one initial sequence, 12 different filler sequences had to be constructed by merely changing the order of the CVs, we were confronted with the mathematical restriction that at least one CV–CV combination within a sequence had to be repeated in order to generate the required number of filler sequences. If anything, this counteracts the Hebb effect of interest to this study, by potentially improving performance for filler sequences. These repeated CV–CV duos were also never used for constructing the nonwords in Experiment 2. For all CV sequences, we also ensured that no existing words were formed each time the order of the CVs was altered.

Procedure

The Hebb procedure was as similar as possible to that of Page, Cumming, Norris, Hitch, and McNeil (2006). The CVs were presented serially, centred on a 15″ monitor, in 48-point bold Arial font. Each CV remained on the screen for 1,000 ms. The interval between the successive CVs was variable. The three CVs within a virtual Hebb nonword followed each other directly, whereas the time interval between virtual nonwords was 2,000 ms. The same timing was used for filler sequences. If participants chose to chunk the information, these spacing parameters would encourage them to make chunks in accordance with the nonwords that we constructed in Experiment 2. If they were to chunk randomly, it would be virtually impossible to find which CVs are combined with which others and, by consequence, to know which nonwords to assemble for Experiment 2. Note that encouraging participants to chunk the CVs in a specified manner may increase the task’s transparency somewhat and therefore trigger explicit learning (in the sense that participants notice the repetition). It has been shown that explicit recognition of the repetition is irrelevant to, and unnecessary for, Hebb learning (e.g., Stadler, 1993), just as it is unnecessary for word learning. Moreover, the very fact that participants become aware of any repetition logically requires some prior "implicit" learning, not least on the first presentation of a to-be-repeated list.

After each sequence, explicit recall was required. On the recall screen, presented immediately after presentation of the last CV, the nine CVs were arranged randomly in a "noisy" circle around a central question mark. Participants were required to recall the CVs in the same order as they were presented by touching them on a touch-screen. This procedure allows that CVs are pointed to more than once, but it does not allow intrusion of CVs that were not presented. The question mark had to be touched in case a CV was omitted, on the position in the list where the omission occurred. After recall, participants were asked to press the space bar in order to start the next trial. Note that the positioning of the CVs around the central question mark was random on each trial. This is of particular importance for the repeated sequences because it avoids the possibility that learning of spatial tapping sequences becomes confounded with Hebb learning.

Results

A CV was scored as correct if it was recalled on the correct order in the sequence. The mean proportion of correctly recalled CVs for the Hebb repetitions and the filler lists are displayed in Figure 1. Regression lines have been added to show the improvement in performance. Two female participants were removed from our sample because 0% of the CVs were remembered correctly after the 12th repetition of the Hebb sequence in both experimental blocks. The Hebb repetition effect was measured by taking the gradient of the regression line of the Hebb repetitions and comparing it to the gradient for the filler lists, for each individual participant. Using the slope associated with the filler sequences as a baseline makes it possible to control for increasing performance originating from task practice rather than Hebb learning. The gradient values were entered into an analysis of variance (ANOVA) with sequence type (filler vs. Hebb) as the independent variable for testing the Hebb repetition effect. The results show that the gradient for the filler sequences ($M = .002$, $SE = .002$) was significantly lower than that for the Hebb sequences ($M = .026$, $SE = .002$), $F(1, 39) = 80.53$, $n_p^2 = .67$, $p < .001$. These results show that a clear Hebb effect was obtained with the nonsense syllables presented in Experiment 1, which is a necessary condition to consider the results of Experiment 2. In this second experiment, we examined whether the materials learnt under Hebb repetition formed representations in the mental lexicon. This was done by means of a classical auditory lexical decision task. This implies that any Hebb influence on nonword processing is a cross-modal effect, originating from abstract phonological representations formed during the learning of recurring series of orthographic (visual) entities. This ensures that any effect of Hebb learning on lexical decision may not, for example, be due to modality-specific traces in episodic memory.

EXPERIMENT 2

Method

Participants

The sample consisted of the same 42 participants as in Experiment 1.

Materials

For the lexical decision (LD) task, we used four types of stimuli: (a) CVCVCV nonwords that were constructed from the CVs of the nonrepeated filler sequences of Experiment 1—for example, "lofodu"; (b) CVCVCV nonwords from the repeated Hebb sequences of Experiment 1; (c) nonwords that were not of the form CVCVCV but had the same length as the other nonwords—for example, "schrak"; (d) Dutch words that were also matched in length—for example, *perzik* (peach). Note that the nonwords that are not of the form CVCVCV were included in order to prevent participants from using a

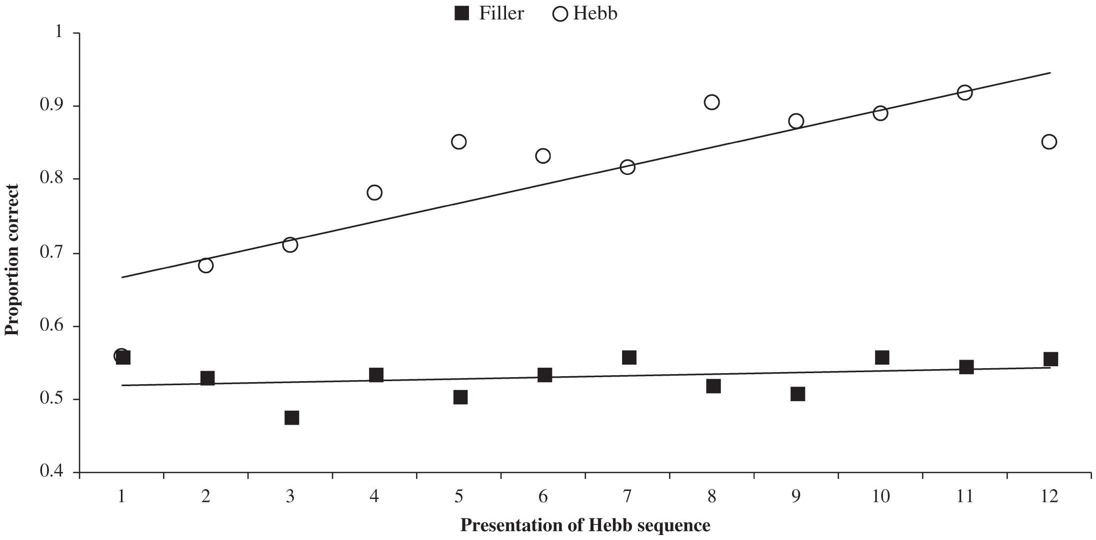

Figure 1. *Mean proportion correct for Hebb lists and matched filler lists in Experiment 1. Regression lines are displayed.*

low-level criterion for the lexical decision—namely, classifying all CVCVCV forms as nonwords. The non-CVCVCV nonwords were phonologically legal Dutch nonwords, generated using the WordGen tool (Duyck, Desmet, Verbeke, & Brysbaert, 2004). In total, 140 words were presented in the LD task. A total of 70 were words, and 52 were non-CVCVCV nonwords. Because two Hebb sequences were used in Experiment 1, and each sequence comprised 3 virtual nonwords, 6 Hebb nonwords were available for the LD task. As there were twice as many different CVs in the filler than in the Hebb sequences, 12 filler nonwords were available for the LD experiment. The fact that filler and Hebb sequences were different for each participant in Experiment 1 also implies that each participant received different filler and Hebb nonwords.

All stimuli for the LD task were digitally recorded in WAV format by a female speaker. The WAV files were all between 750 and 850 ms of duration, with an average of approximately 800 ms. In order to match the presentation time of the stimuli for the LD, we edited the WAV files in sound-editing software (WaveLab) and transformed them into files of exactly 800 ms, without any audible loss of quality.

Procedure

In the 5-minute period between experiments, the administrative requirements of the experiment were fulfilled, so that participants' short-term memory was cleared from the presented materials. The stimuli for the LD task were presented auditorily through closed headphones (Sennheiser HD 265-1) at 60 dB. The presentation time was 800 ms, followed by a fixed interstimulus interval of 2,500 ms. Participants were required to decide as fast and accurately as possible whether the stimulus was a word or a nonword, by pressing a key on a response box.

Results

We ignored the LD data of the 2 participants that were discarded from the analysis of Experiment 1. The data of the remaining participants were subjected to an outlier analysis in which all response times (RTs) that deviated more than 2.5 standard deviations from the overall mean were removed. This outlier analysis, which was performed for the words and nonwords separately, resulted in a data reduction of 2.1%. Mean RTs and accuracy in the four different stimulus conditions of the LD task are presented in Table 1.

Table 1. *Mean response times and accuracies in the four different stimulus conditions of the lexical decision task used in Experiment 2*

Condition	*RT (ms)*	*Accuracy (%)*
Word	959 (12)	90.93 (0.89)
Nonword	1,003 (11)	94.47 (0.86)
Filler nonword	951 (12)	97.92 (0.72)
Hebb nonword	978 (16)	96.66 (1.60)

Note: Standard errors are in parentheses.

An ANOVA with condition (words, nonwords, filler nonwords, Hebb nonwords) as the independent variable reveals a significant main effect, $F(3,\ 17) = 12.83$, $n_p^2 = .43$, $p < .001$. Planned comparisons show that the Hebb nonwords yielded reliably slower RTs than the filler nonwords, $F(1,\ 39) = 5.65$, $n_p^2 = .13$, $p < .05$. The latter result shows that participants were slower in rejecting the nonwords constructed from the Hebb sequences in Experiment 1 than the nonwords from the filler sequences. This suggests that repeated sequences during Hebb learning developed long-term representations in the mental lexicon. These lexical representations inhibited classification of the Hebb nonwords as nonexisting Dutch words. Note that the non-CVCVCV nonwords yielded slower RTs than both Hebb and filler nonwords. This is most probably a consequence of the fact that both filler and Hebb nonwords were CVCVCV sequences whereas the third kind of nonwords were not. Because word targets were also not of the form CVCVCV, we had to include other non-CVCVCV nonwords to prevent a LD strategy in which participants used syllabic structure as a low-level criterion for word classification, instead of lexical search. Also note that of the 40 participants, 12 reported not having been aware of the repeating lists in Experiment 1. The LD data of those 12 participants (implicit learners), were comparable to those of the 28 participants that were aware (explicit learners; interaction of condition with a factor implicitness, $F < 1$).

DISCUSSION

It has been assumed for a long time that a strong association exists between measures of short-term verbal serial recall and the acquisition of novel words (e.g., Baddeley et al., 1998), although direct transfer between these two functions has never been experimentally demonstrated. We used the Hebb repetition paradigm as a link between immediate verbal serial recall and word-form learning. We demonstrated that what is learnt during immediate recall of ordered phonological information constitutes a similar representation in the mental lexicon as does a newly acquired word. This shows that the Hebb repetition effect may be considered a laboratory analogue of word learning. Most importantly, it also indicates that the ability of phonological working memory to deal with order and item information, being able to represent an ordered sequence of information for a short period of time, constitutes the basis for human word-form learning—that is, the development of lexical representations. These observations supplement recent correlational work by Mosse and Jarrold (2008), who observed that the magnitude of Hebb learning for both verbal and spatial materials correlates with performance on a nonword paired-associate learning task, and who therefore concluded that the acquisition of novel word forms may rely on the domain-general ability of representing serial order in working memory.

It is important to realize that the current findings (slower RTs for Hebb than for filler nonwords) may not be due to higher familiarity with the Hebb than with the filler items, since the CVs in the Hebb and filler sequences have been presented an equal number of times.[1] What the different lexical decision RTs between filler and Hebb nonwords do reflect, according to Page and Norris's (2008) model of the Hebb effect, is that long, temporally grouped lists of CVs are likely to be learned as sequences of chunks, with

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[1] Also note that the LD results may not easily be explained in terms of higher familiarity with the (auditory) Hebb nonwords, as these nonwords have never been presented as an entity on its own in the visual Hebb experiment.

the chunks delimited by the temporal grouping structure. In this model, as in its predecessors, the learning of a chunk comprises the addition to memory of a new, localist representation that activates when its constituent items are presented in the correct order. Repeated activation of this sort permits increasingly accurate recall of the list items within a chunk (see Page & Norris, 2008, for implementational details). Ultimately, the recall of all the items within a chunk can be achieved via the activation of the single chunk representation (cf. Miller, 1956), rather than by the separate activation of representations corresponding to the individual list items. From this perspective, a newly learned word-form is simply a chunked sequence of sublexical items (in this case, two-letter syllables), and it is for this reason that the CVCVCV-chunks learned in the Hebb repetition phase (Experiment 1) are harder to reject than are controls, in the lexical decision phase (Experiment 2). And because the same stimuli were used as filler nonwords and Hebb nonwords across participants, these effects may not have originated from item-specific particularities. In addition, the observation that the LD results were comparable for both implicit and explicit Hebb learners shows that lexicalization of the Hebb materials can, like language learning, also occur in an implicit manner (see Saffran, Aslin, & Newport, 1996, for a striking demonstration of incidental word learning by 8-month-old infants in a segmentation task).

The fact that we were able to induce gradual development of short-term to long-term representations across modalities (i.e., visual Hebb presentation and auditory lexical decision) corroborates the robustness of our findings. More importantly, at a theoretical level, this cross-modal effect illustrates that the long-term representations established during Hebb learning are of an abstract, phonological nature, even though Hebb materials in Experiment 1 were presented as visual, orthographic forms. This has great theoretical relevance because it illustrates that phonological lexical representations develop early and automatically during word acquisition, even if language exposure occurs exclusively through orthographic word forms. This is consistent with Frost's (1998) principle of nonneutral lexical representations (see the Introduction) in the psycholinguistic literature, which states that entries in the mental lexicon are of a phonological nature. In this view, the present findings illustrate the prominent role of phonology, not only during the processing of language, but also during the acquisition of language.

In summary, by demonstrating that the Hebb repetition effect "mimics" natural word learning, we have made the relation between short-term serial recall and language learning more explicit by arguing that word learning depends on the same mechanism that is used to retain ordered sequences of phonological information for a short period of time. These findings increase the ecological relevance of the great amount of experimental work and theoretical knowledge regarding phonological working memory. As such, this study bridges the gap between the working-memory literature and psycholinguistics.

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