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The Resilience of Verbal Sequence Learning: Evidence from the Hebb Repetition Effect

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RUNNING HEAD: The Resilience of Verbal Sequence Learning

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Abstract

In a single large-scale study, we demonstrate that verbal sequence learning as studied using the classic Hebb repetition effect (Hebb, 1961)—the improvement in the serial recall of a repeating sequence compared to non-repeated sequences—is resilient to both wide and irregular spacing between sequence repetitions. Learning of a repeated sequence of letters was evident to a comparable degree with three, five, and eight intervening non-repeated sequences and regardless of whether the spacing between repetitions was regular or irregular. Importantly, this resilience of verbal sequence learning was observed despite the fact that there was complete item-set overlap between repeated and non-repeated sequences. The findings are consistent with the conceptualization of the Hebb repetition effect as a laboratory analogue of natural phonological word-form learning. The results also have implications for the two leading models of Hebb sequence learning: Whereas the results are incompatible with the model of Page and Norris (2009), they can be handled readily by the model of Burgess and Hitch (2006) through the abandonment of its assumption of long-term (across-trial level) decay.

KEYWORDS: Verbal sequence learning; Hebb effect; Word-form learning; Serial memory; Serial recall

The processing of serial order has long been considered one of the core components of human cognition (e.g., Hurlstone, Hitch, & Baddeley, 2014; Lashley, 1951; Marshuetz, 2005). The learning and subsequent use of sequences of stimuli or actions underpin most if not all skilled behavior: language, music, dance, sport, and problem solving are just a few domains in which sequence learning is fundamental. In the verbal domain, for example, the perception and retention of an initially novel sequence of elements (e.g., phonemes, syllables, words) and the transition from a short-term representation of the sequence to long-term knowledge is an essential aspect of language acquisition (e.g., Baddeley, Gathercole, & Papagno, 1998; Estes, 1985; Gupta, 2003, 2009). A widely used laboratory phenomenon through which sequence learning in the language domain has been studied is the *Hebb repetition effect* whereby short-term serial recall of a verbal sequence (e.g., of letters, words, digits, or syllables), presented visually or auditorily, is enhanced if that sequence is repeated intermittently across a block of trials compared to that for non-repeated sequences (e.g., Baddeley & Warrington, 1970; Couture, Lafond, & Tremblay, 2008; Cumming, Page, & Norris, 2003; Hebb, 1961; Melton, 1963; Oberauer & Meyer, 2009). This development of a long-term representation of the repeated sequence has been argued to tap the same mechanism that underpins the learning of the novel order of phonemes that comprise a newly encountered word. That is, the Hebb effect is thought to constitute a laboratory analogue of phonological word-form learning, providing an invaluable tool in the study of language acquisition (e.g., Mosse & Jarrold, 2008; Page, Cumming, Norris, McNeil, & Hitch, 2013; Page & Norris, 2008, 2009; Szmalec, Duyck, Vandierendonck, Mata, & Page, 2009). However, the extent to which the Hebb repetition effect can be considered a valid analogue of phonological word-form learning remains to be established. In the present study, we examined whether Hebb repetition learning exhibits two key properties of naturalistic word-form learning: a resilience to both wide and irregular spacing between the repetitions of the critical sequence. The answer to this question also has important implications for prominent computational models of verbal sequence learning that have been based on Hebb repetition learning.

The Word-Form Learning Analogy (W-FLA) Hypothesis

Several observations regarding the Hebb repetition effect in verbal serial recall support the hypothesis that it may constitute a laboratory analogue of word-form learning (Page & Norris, 2008, 2009). One is its parsimony: It seems unlikely that the mechanisms involved in learning a novel sequence of letters, words, or digits presented for short-term serial recall are fundamentally different from those involved in the learning of the novel sequence of phonemes or syllables that constitute a newly encountered word. It is reasonable, for example, to suppose that recalling and learning the list of letters “B, R, J, Q” is akin to recalling and learning the new word “Beearjaycue” (Page & Norris, 2009). Indeed, this reasoning is supported by the fact that verbal serial recall bears strong empirical similarities to the ability to immediately repeat a nonword (Gupta, 2005); it thus seems highly plausible that the long-term learning of the two kinds of novel sequence also shares at least some basic mechanisms in common (Page & Norris, 2008). Numerous other characteristics of the Hebb effect are consistent with the hypothesis: Several repeating sequences can be learned at the same time, at least when there is no overlap in the identity of the items in the repeating and non-repeating sequences, and once a repeating sequence is learned, the representation is highly stable, conferring a recall and recognition advantage at least four months after its last presentation (Page et al., 2013). All these properties must also be exhibited by any functional word-form learning system. However, the first goal of the present study was to re-examine one of the oldest and well-accepted empirical characteristics of the Hebb effect but which, on the face of it, is highly problematic for the hypothesis: that the effect is lost if the spacing between repetitions of the critical sequence is relatively wide.

The Role of Repetition-Spacing

In a classic paper, Melton (1963) reported that there is no Hebb repetition learning if there are more than five non-repeated sequences between each instance of the repeating sequence (specifically, he found that there was learning with six- but not nine-trials apart spacing). This appears to render the word-form learning analogue hypothesis a non-starter: vocabulary acquisition would be extremely slow if a new word had to be repeated at least every sixth word to build upon any learning that occurred the last time it was encountered. However, it has since been claimed that Melton's (1963) result was predicated on the use of permutations of a small closed-set of items (the digits *1-9*) for both the repeating and non-repeating lists (as used also in Hebb's, 1961, original study). Page et al. (2013) established recently that the Hebb effect survives much wider repetition-spacing—with a repetition only every twelfth trial—so long as there is no overlap between the items comprising the repeating and non-repeating lists (see also Melton, 1967). That Hebb repetition learning is not, after all, impeded by wide spacing when there is little or no overlap between the repeating and non-repeating sequences seems, therefore, to provide a reprieve for the W-FLA hypothesis on the grounds that different words are rarely phonological anagrams of one another (Page & Norris, 2008, 2009; Page et al., 2013).

However, while it is true that words are not often phonological anagrams of each other, it can be argued that a Hebb repetition effect with little or no overlap between repeating and non-repeating sequences (Page et al., 2013) is not a true Hebb repetition effect. Historically, from Hebb's (1961) and Melton's (1963) seminal studies onwards, the Hebb paradigm has been concerned specifically with *sequence* learning and, accordingly, the vast majority of studies have involved sequences (both repeated and non-repeated) that constitute permutations of the same small set of items, precisely so as to rule out item-level influences on the learning of the repeating sequence (e.g., Baddeley & Warrington, 1970; Couture et al., 2008; Hebb, 1961; Melton, 1963;

O'Shea & Clegg, 2006; Parmentier, Maybery, Huitson, & Jones, 2008). When the items used for the repeating and non-repeating sequences are non-overlapping (Page et al., 2013), at least part of the repetition effect may be driven by what might be called item-set learning; the learning of which items can co-occur within a sequence across the experimental session, not the particular sequence in which they occurred. That is, an increase in the probability of remembering which items are appropriate candidates for output on a given trial will systematically increase the item-in-correct-position score. Thus, it may be item-set learning that survives wide repetition-spacing (cf. Page et al., 2013) not the Hebb repetition effect per se. While item-set learning is in itself likely to be useful in word-form learning (i.e., learning which phonemes tend to co-occur in words), the learning effect with non-overlapping sequences fails to hermetically isolate the learning of sequence information per se.

There are, in any case, reasons to doubt the long-held assumption that there is no pure Hebb repetition learning (i.e., with item-set overlap between repeating and non-repeating lists) with wide repetition-spacing. In Melton's (1963) study, there were only three repetitions of the critical sequence. It remains possible, therefore, that pure Hebb repetition learning does occur with wide spacing but that it is weaker or slower to manifest than with narrow spacing and would therefore take a relatively large number of sequence-repetitions for the effect to be observable.[1] This is important because the absence of learning has very different theoretical ramifications from that of slow learning, especially as it may be the behavioral expression of learning that is slow, not its actual occurrence; that is, the learning may be latent (e.g., Thistlethwaite, 1951; Tolman, 1948). So in relation to phonological word-form learning, for instance, an infant may be

[1] For reasons that are not clear, in Page et al.'s (2013) conceptual replication of the standard narrow repetition-spacing with complete item-set overlap condition (i.e., every third list; Hebb, 1961; Melton, 1963), the Hebb effect was unreliable. As a result, their findings are moot with regards to the possible influence of repetition-spacing on the Hebb effect with complete item-set overlap.

learning words with behavioural evidence of this only becoming apparent later. Whether or not pure Hebb repetition learning survives wide repetition-spacing is also important for the veracity of the W-FLA hypothesis: whilst complete phonological anagrams are rare, many words necessarily have some phonemes and phoneme-sequences in common; a language learning process that could not deal with such overlap with wide repetition-spacing would not be functional.

The question of whether or not pure Hebb repetition learning is found with wide spacing also has important implications for computational models of verbal sequence learning that have been based on the Hebb repetition effect (Burgess & Hitch, 1999, 2006; Page & Norris, 2009). In Page and Norris' (2009) extension of their primacy model of serial recall (Page & Norris, 1998), in which serial order is represented directly via a primacy gradient of activation across successive list items, long-term sequence learning proceeds in the following way: Any list presented for short-term serial recall initially activates several uncommitted 'chunk' representations; at this stage, one of these becomes "engaged" in response to a particular list but not fully committed. With subsequent presentations of the same list, that engaged chunk representation becomes increasingly preferentially activated in response to that list, to the extent that it eventually becomes 'fully committed' to it and increasingly facilitates its short-term serial recall. Crucially, this hooking up of a chunk representation with a given list is a competitive process: Several chunk representations (whether uncommitted, engaged, or fully committed) compete with one another to represent a given list. This is important to account for the gradual nature of Hebb repetition learning: Initially, the chunk representation that becomes engaged to a given list will not be highly differentiable from other chunk representations that are uncommitted or that have become engaged to other lists (either a different repeating list or a filler list). With further repetitions of a given list, however, the extent to which a given chunk representation uniquely matches that list increases until that chunk representation will activate strongly and exclusively for that list and will suffer little interference from other competing chunk representations.

Most important given our concerns in the present article is that the competitiveness of the hooking-up process in the Page and Norris (2009) model is also critical for accounting for the absence of learning when all lists in a Hebb experiment comprise permutations of the same set of items with relatively wide repetition-spacing (Melton, 1963). In the model, the distinction between the chunk representation engaged to a to-be-repeated list and chunk representations that become engaged to filler lists is very weak under these conditions because the filler lists are perfect anagrams of the to-be-repeated list. Thus, with a repetition-spacing of 6 trials-apart (Melton, 1963), when the critical list is repeated for the first time, there are five chunk representations—those that have become engaged but not fully committed to the five intervening filler lists—that will compete strongly with the chunk representation that became engaged to the repeating list. The competition would be so strong that it would not be resolvable before the short-term representation of the current repeated list has decayed and hence the opportunity to learn that list (i.e., to associate it with any single chunk representation) would be precluded. Moreover, the degree of competition only intensifies as a block of trials proceeds given that an increasing number of chunk representations associated with filler lists would be generated between each repetition: "It becomes progressively more difficult to ensure relatively rapid learning under circumstances in which large numbers of anagram lists are present and being partially learned" (Page & Norris, 2009, p. 3747). And indeed, computer simulations have confirmed that the model fails to learn a repeating list, even if that list is repeated seven times, with relatively wide repetition-spacing (6 trials-apart or more) and complete item-set overlap between repeating and non-repeating lists (Page & Norris, 2009). Thus, if we were to find a Hebb repetition effect with complete item-set overlap and wide repetition-spacing in the present study, this leading model of Hebb repetition learning would clearly require modification.

A second model of Hebb repetition learning is based on an extension of a class of models of short-term serial recall in which item-order is represented through item-context representations (Burgess & Hitch, 1999, 2006). The model posits two types of connection-weights between each item in a list and its position in that list: one is strong but short-lasting and underpins the short-term serial recall of a list while the second is weak but long-lasting and underpins the gradual long-term learning of a repeating list. Of particular interest for present purposes is that the "…assumption that slow weights also decay...provides a natural account of the observation that the Hebb Effect is contingent on there being only a small number of 'filler' lists separating successive presentations of the repeated list (Melton, 1963)." (Burgess & Hitch, 2006, pp. 632-633; see also Hitch, Flude, & Burgess, 2009). That is, the repetitions of the critical sequence must occur within a certain period (or after a certain number of intervening lists) because otherwise the long-term item-position weights will have decayed before they can be reinforced: Again, therefore, the first question we address here of whether the pure Hebb repetition effect is indeed contingent on relatively short repetition-spacing would have implications for a basic assumption of this model.

The Role of Repetition-Regularity

Our second objective in the present article is to examine for the first time the possible role of the *regularity* of spacing between repetitions of the critical sequence (again, with complete item-set overlap between repeating and non-repeating sequences as in the standard paradigm). To our knowledge, in all studies to date, whichever repetition-spacing has been used, that spacing has been fixed for a given repeating sequence across an experimental block. Thus, it has yet to be established whether such regularity is necessary for Hebb repetition learning or whether it at least augments it. It is plausible that even when Hebb repetition learning is implicit (cf. Stadler, 1993), the cognitive system detects the regularity and this facilitates the recognition of the repeating sequence and hence its enhanced recall. For example, there is evidence that participants become attuned to the temporal regularity of the content presented across a series of serial recall trials even when that content is task-irrelevant, as evidenced by involuntary attentional capture by that content when the regularity is broken (Vachon, Hughes, & Jones, 2012). If regular spacing is indeed necessary for Hebb repetition learning, this would render the W-FLA hypothesis untenable given that a new word is highly unlikely to be encountered repeatedly with the same number of other, intervening, new words. As with the role of repetition-spacing, the question of whether or not the regularity of spacing influences Hebb repetition learning also has implications for the models of the Hebb effect outlined earlier. Thus, for the Page and Norris (2009) model, with irregular spacing, as soon as two successive instances of the critical sequence are spaced wider than the point at which the competition between chunk representations becomes particularly great (at 6 trials-apart or more), learning at that repetition should be precluded, meaning that the learning process would be postponed until the next time two successive instances of the list are relatively close to one another. Thus, Hebb repetition learning should be dramatically attenuated with irregular spacing, at least when the average spacing between repetitions is six-trials apart or more. The same prediction holds for the Burgess and Hitch (1999, 2006) model: As soon as a repetition is delayed by more than 6 trials, the long-term connection-weights between items and their serial positions would have decayed, meaning that learning would have to wait for another, more narrowly-spaced, repetition in order to re-initiate.

The present study, then, involved simultaneous manipulations of repetition-spacing and repetition-regularity in a large between-participants experiment involving 210 participants. Instances of the Hebb sequence were either 4 trials apart (i.e., 3 intervening lists), 6 trials apart (i.e., 5 intervening lists), or 9 trials apart (i.e., 8 intervening lists). In the regular spacing condition, the number of intervening lists was fixed throughout the experimental block while in the irregular spacing condition, the number of intervening lists varied, though the average spacing was also (very close to) either 4-, 6-, or 9-trials (see Method for details). In all conditions, the Hebb sequence was presented twelve times (i.e., repeated eleven times), a greater number than the majority of Hebb repetition studies and, most notably, much greater than Melton's (1963) four presentations.

In terms of the models discussed above, in the 4 trials-apart condition, all repetitions in the regular spacing condition were well within the threshold for reinforcing either the hooking-up of the repeating list with a given chunk representation (Page & Norris, 2009) or the association between the list and a given set of positional codes (Burgess & Hitch, 2006). In the irregular spacing condition, some repetitions would be above the threshold (up to 7 trials-apart) while some would be within it; thus, the models would predict a strong Hebb repetition learning in the regular spacing condition and weaker learning in the irregular spacing condition, but learning nonetheless.

In the 6 trials-apart condition, the converse prediction holds: all repetitions in the regular spacing condition would be above the reinforcement threshold while in the irregular condition approximately half the repetitions would be within the threshold whilst others would be well above it (up to 11 trials-apart); thus, the models predict no learning in the regular spacing condition but some (albeit weak) learning in the irregular spacing condition.

Finally, in the 9 trials-apart condition, the models again predict no learning in the regular condition but some—now very weak—learning in the irregular condition. In contrast, to the predictions of these computational models of the Hebb effect, if (pure) Hebb sequence learning is a valid analogue of word-form learning, such learning should be resilient not only to wide spacing but also to irregular spacing.

Method

Participants

Two-hundred and ten students from Université Laval participated in exchange for a small honorarium. All reported normal or corrected-to-normal vision.

Design

The experiment had a mixed factorial design with three factors. The within-participant factor was List-type: repeated or non-repeated. The first between-participants factor was Repetition-spacing, with three levels (with 70 participants allocated to each): Whether the actual or average (see below) spacing between repetitions was 4 trials-apart, 6 trials-apart, or 9 trials-apart. The second between-participants factor was Repetition-regularity: Half the 70 participants in each repetition-spacing condition received the repeated sequences with fixed spacing while the other half received them with variable spacing but with the average spacing being approximately the same as for the fixed-spacing condition.

Material

All sequences—both repeated and non-repeated—were nine items long and comprised random permutations of the letters *D, F, G, H, K, L, N, R,* and *Q* presented successively (700 ms on, 300 ms off) in black font on a white computer screen. An experimental session for a given participant involved one block of trials made up of 12 ‘sub-blocks’ each containing either 4 trials, 6 trials, or 9 trials depending on the Repetition-spacing condition to which the participant was assigned. Each sub-block consisted of one instance of the critical repeating sequence, the remaining trials featuring unique, non-repeated, sequences. The repeated sequence was presented on the fourth trial of each sub-block in the regular spacing condition, while in the irregular condition it was randomly assigned to one of the four trials of each sub-block (mean number of non-repeated sequences between the repeated sequence: 3.01, *SD* = 1.65). The same arrangement was applied to the 6 trials- and the 9-trials-apart conditions with the restriction that in the irregular condition there were at least two non-repeated trials interleaved between repeated trials. The mean number of non-repeated sequences between repeated sequences in the irregular condition with 6 trials-apart spacing was 5.09 trials, *SD* = 2.10, while that in the irregular condition with 9 trials-apart spacing was 8.01 trials, *SD* = 3.51). Regardless of repetition-regularity condition, there were 48 trials in total in the 4 trials-apart condition, 72 in the 6 trials-apart condition and 108 in the 9 trials-apart condition.

Procedure

Participants were tested individually and the experiment lasted about 30 min in the 4 trials-apart conditions, 40 min in the 6 trial-apart conditions, and 60 min in the 9 trials-apart conditions. Participants were seated approximately 60 cm from the screen. They were told that the purpose of the experiment was to investigate verbal immediate serial recall and that they had to recall nine letters in the order in which they were presented by writing down the sequence on an answer sheet (note that they were unable to see their responses to previous sequences). Participants were instructed to write the sequence in presentation order, starting with the first letter presented, then the second, and so on, and to refrain from returning to change an item after it had been written down. Participants were told to leave a blank if they could not remember an item in a given serial position. Trials were self-paced; participants pressed the space bar to start the next trial. Two non-repeated practice sequences were presented before the experimental trials.

The study received ethical approval from the ethics committee of the School of Psychology, Université of Laval.

Results

The serial recall data were scored according to the standard correct-in-position criterion: a response was only recorded as correct if the item was recalled in the same absolute serial position as that in which it was presented. Hebb repetition learning was then assessed by comparing the gradient of improvement in serial recall performance (collapsed across serial positions) across the instances of the repeating sequence to any gradient of improvement in the recall of non-repeated sequences. A significantly steeper improvement gradient for the repeated compared to non-repeated sequences would indicate Hebb repetition learning over and above any general practice effect. For the statistical analysis, the dependent variable was the gradient value of the regression line fitted to the number of items each participant correctly recalled across each instance of the critical, repeating, sequence and the gradient value of the regression line fitted to the number of items each participant recalled on average for the non-repeated sequences within each of the 12 sub-blocks. The greater the gradient value (ranging from 0 to .89 in the present experiment), the greater the improvement in serial recall performance across sub-blocks. This is a popular measure in this paradigm because it captures any learning of the repeating sequence over and above any general task-practice effect that would be evidenced by improvement across the non-repeated sequences (e.g., Page et al., 2006; Parmentier et al., 2008).

Figure 1 shows the data from the regular- and irregular-spacing conditions as a function of repetition-spacing condition. A 3 (Repetition-spacing: 4-, 6-, or 9-trials apart) x 2 (Regular or irregular spacing) x 2 (List-type: repeated or non-repeated) mixed ANOVA showed that there was Hebb repetition learning: the gradient of improvement for the recall of the repeated sequence was greater overall than for the non-repeated sequences, $F(1, 204) = 65.11$, $p < .001$, $\eta^2_p = .242$. There was no main effect of either Repetition-spacing, $F = 1$, $p = .37$, $\eta^2_p = .01$, or Repetition-regularity, $F(1, 204) = 1.86$, $p = .17$, $\eta^2_p = .009$, and no interaction between Repetition-spacing and Repetition-regularity, $F < 1$. Of greater interest, there was also no interaction between List-type and Repetition-spacing $F(2, 204) = 2.43$, $p = .09$, $\eta^2_p = .023$, nor between List-type and Repetition-regularity, $F = .003$, $p = .96$, $\eta^2_p < .0001$. The three-way interaction was also not significant, $F < 1$.

Although there were no significant interactions in the overall ANOVA, we deemed it prudent to scrutinize further both the absence of an interaction between List-type and Repetition-spacing and the absence of an interaction between List-type and Repetition-regularity, given their centrality to the hypotheses of interest. First, an ANOVA focused only on the data from the regular spacing groups ($n = 105$) showed that there was again no interaction between List-type and Repetition-spacing, $F(2, 102) = .70$, $p = .5$, $\eta^2_p = .013$. We also subjected this List-type by Repetition-spacing interaction (or lack thereof) to a Bayesian analysis (cf. the Bayesian approximation procedure; Wagenmakers, 2007) given the difficulty of making arguments based on a null effect/interaction with null hypothesis testing. Using the procedure described in Masson (2011), we used the sums of squares from the 2x3 ANOVA just reported to generate the posterior probability of the null hypothesis. The probability of the null hypothesis, $P_{BIC}(H_0|D)$, was .98, indicating “strong” support for the null hypothesis according to Raftery’s (1995) labelling scheme. Second, we conducted an ANOVA focused on the possible effect of Repetition-regularity on the Hebb effect, collapsing across the Repetition-spacing factor [i.e., a 2(List-type) x 2(Repetition-regularity) mixed ANOVA]. Again, there was no interaction between the two factors, $F(1, 68) < .0001$, $p = .99$, $\eta^2_p < .0001$, with a Bayesian analysis indicating “positive” support (cf. Raftery, 1995) for the null hypothesis, with $P_{BIC}(H_0|D) = .89$.

Follow-up *t*-tests confirmed a Hebb repetition effect for all groups of participants: in the 4 trials-apart condition with regular spacing, $t(34) = 3.930$, $p < .001$, and irregular spacing, $t(34) =$

4.145, $p < .001$; in the 6 trials-apart condition with regular spacing, $t(34) = 2.532$, $p = .016$, and irregular spacing, $t(34) = 3.163$, $p = .003$; and in the 9 trials-apart condition with regular spacing, $t(34) = 3.190$, $p = .003$, and irregular spacing, $t(34) = 2.716$, $p = .01$.[2]

Finally, while it may seem from Figure 1 that learning was attenuated in the 9 trials-apart condition with regular spacing at the first four sub-blocks—mapping onto the number of repetitions of the Hebb sequence in Melton (1963)—a further statistical analysis focused on this possibility again failed to support it: There was again no significant interaction between List-type and Repetition-spacing when only the first four sub-blocks were included in the analysis; moreover, a Bayesian analysis indicated "strong" support, $P_{BIC}(H_0|D) = .97$, for the null hypothesis.

Discussion

The present results establish that verbal sequence learning—as witnessed in the form of Hebb repetition learning—is highly resilient: It occurs with both wide repetition-spacing (with repetitions of at least 9 trials-apart) and irregular spacing between instances of the critical, repeating, sequence, even with the standard paradigm in which there is complete item-set overlap between repeating and non-repeating sequences. In relation to repetition-spacing, not only was there a Hebb effect with 9 trials-apart spacing, there was no statistical evidence for any reduced learning effect with such spacing compared to 6 or 4 trials-apart spacing.

The resilience of pure Hebb repetition learning to wide repetition-spacing is consistent with the hypothesis that such learning constitutes a laboratory analogue of word-form learning

[2] An analysis using the Levenshtein edit-distance metric (see Kalm & Norris, 2016) yielded almost identical results. In summary, the gradients of improvement using this metric were as follows: In the regular spacing condition they were $M = .1889$, $M = .1627$, and $M = .2121$ for the repeated sequence, and $M = .0641$, $M = .0844$, and $M = .0864$ for the non-repeated sequences, respectively for the 4-trial blocks, the 6-trial blocks, and the 9-trial blocks conditions. In the irregular spacing condition, the gradients were $M = .1662$, $M = .1476$, and $M = .1498$ for the repeated sequence, and $M = .0411$, $M = .0589$, and $M = .0897$ for the non-repeated sequences, respectively for the three spacing conditions.

(Mosse & Jarrold, 2008; Page & Norris, 2008, 2009; Szmalec et al., 2009): It is likely that in the natural linguistic environment, an infant will encounter many intervening old or other new words between repetitions of any given new word but is nonetheless clearly able to acquire and eventually reproduce its phonological form with relative ease. Our findings also overturn the long-held assumption based on Melton's (1963) early finding (see, e.g., Baddeley & Warrington, 1970; Burgess & Hitch, 1999; 2006; Couture et al., 2008; Cumming, Page, & Norris, 2003; Fritzen, 1972; Hitch et al., 2009; Page et al., 2013; Page & Norris, 2008, 2009; Turcotte, Gagnon, & Poirier, 2005) that Hebb repetition learning is absent with wide repetition-spacing (6 trials-apart or more). Furthermore, contrary to Page et al. (2013), this is the case even when there is complete item-set overlap between repeated and non-repeated sequences. Indeed, if learning with wide repetition-spacing was restricted to sequences with no item-set overlap, this would be problematic for the W-FLA hypothesis. Page and Norris (2009) were satisfied with the Hebb effect being absent with wide repetition-spacing in a high item-set overlap situation on account of "the low likelihood that repeated presentations of a to-be-learned word form would be separated by other (also unfamiliar) word forms that were its phonemic 'anagrams'". While this is true—words are rarely perfect phonological anagrams of one another—words are nevertheless made up of a relatively small set of phonemes (e.g., around forty-four in English; Jenkins, 2000) and thus there is inevitably a fair amount of phonological overlap between words. Particularly germane to the W-FLA hypothesis is that this is especially the case during the acquisition of an infant's first words (e.g., "mammy/mummy", "daddy"; "dummy"; "dolly") when the phonemic inventory is relatively small (e.g., Matthews & Brown, 1997; Velten, 1943). Thus, from this standpoint, the present results are far more favorable toward the W-FLA hypothesis than are those of Page et al. (2013).

Also favorable to the W-FLA is our novel demonstration that Hebb verbal sequence learning is resilient to irregular spacing between repetitions even under conditions in which the average spacing was approximately 9 trials-apart (and where some of the repetitions were 16 trials apart). This result is also highly welcome from the standpoint of the W-FLA hypothesis given that it would be rendered untenable if Hebb sequence learning was heavily reliant on regular spacing; clearly, in the infant's linguistic environment, a given new word is not repeated at highly fixed, regular, intervals. There was also no evidence of any attenuation of learning with irregular spacing. Thus, it seems either that participants do not implicitly (or indeed explicitly) register the regularity in the standard paradigm or that, if they do, this does not facilitate learning.

The present results are also at odds with the predictions of the two current models of verbal sequence learning that are based on the Hebb repetition effect (Burgess & Hitch, 1999, 2006; Page & Norris, 2009). Both were built in such a way as to accommodate the (incorrect) assumption that no such effect occurs with wide repetition-spacing under complete item-set overlap conditions. Thus, Burgess and Hitch (1999, 2006) included the notion that the long-term connection weights between items and their list-positions are subject to a slow decay process to accommodate this assumption. However, it has been suggested, in light of the present data, that the long-term decay component could simply be abandoned as it was included in the model *only* to accommodate Melton's (1963) finding (N. Burgess, personal communication, November, 2017). Indeed, while the long-term decay component was retained in the latest version of the Burgess and Hitch (2006) model (see also Hitch et al., 2009), it was found to be redundant for the particular simulations reported in the Burgess and Hitch (2006) article. Thus, the present data, in overturning the conclusions of Melton (1963), indicate that the Burgess and Hitch (2006) model is more parsimonious than previously thought. Dropping the long-term decay component of the model also allows it to accommodate the resilience of the Hebb effect to irregular repetition-spacing as that effect would only be problematic for the model insofar as, for all groups, such irregular spacing would have involved some instances of (on occasion very) wide spacing between repetitions. Without long-term decay in the model, this effect no longer poses a difficulty either.

One might ask, however, whether the Burgess and Hitch (2006) model is still challenged by the present data insofar as this version of the model (unlike that of Burgess & Hitch, 1999) incorporates the assumption of competition between multiple item-context sets, each representing a sequence the model has learned previously. To elaborate, as a sequence is presented, the model attempts to match that input against all previous context sets. As each item in a sequence is presented, the cumulative match to each context set is maintained and sets with a cumulative match that falls below a certain threshold are rejected. Until all non-matching context sets are rejected, however, competition between context sets to represent the current sequence will ensue and hence potentially interfere with learning a repeating (Hebb) sequence. In principle, this means that the greater the number of non-repeated sequences between each instance of the repeated sequence--particularly with complete item-set overlap as was the case in the present study--the more context-sets and hence interference there should be with the recall and learning of the repeated sequence. In practice, however, the effect of the repetition-spacing implemented across the conditions of the current study (4 trials-apart vs. up to 9 trials-apart in the regular-spacing condition and up to 16 trials apart in the irregular-spacing condition), would be minimal. This is because the level of competition in the model is set such that learning of a repeated list can occur despite the hundreds if not thousands of similar sequences that an individual would likely have encountered in their lives prior to the start of the experiment (N. Burgess, personal communication, December, 2017; see also Simulation 5 in Burgess and Hitch, 2006). Thus, the difference in the amount of competition from 15 non-repeated sequences compared to 3 non-repeated sequences would be negligible and empirically undetectable. Indeed, if the competitive cumulative matching process had alone been able to account for the (apparent) effect of repetition-spacing (Melton, 1963), there would be no reason to have retained the long-term decay component within the 2006 model at all.

The model of Page and Norris (2009), in contrast to Burgess and Hitch (1999, 2006), uses interference (or competition) as the key mechanism underpinning the effect of repetition-spacing as originally reported by Melton (1963) and its interaction with the amount of overlap between items in the repeated and non-repeated sequences (Page et al., 2013). As noted earlier, with complete item-set overlap, the model fails to learn with repetition-spacing of 6 trials-apart or more, in marked contrast to the present data in which learning was evident even with 9 trials-apart repetition-spacing. It is only able to accommodate learning with such wide repetition-spacing when there is no overlap between repeated and non-repeated sequences (Page et al., 2013). This model also, therefore, requires modification in light of our data. One possibility is that the interference function could be made less powerful to allow learning with complete item-set overlap with wide repetition-spacing. However, this apparent solution is complicated by the fact that there was no evidence of an attenuation of learning between the 4 trials-apart and 9 trials-apart conditions in the present experiment. That is, there was no evidence of any interference at all. This in turn raises the question of whether the key piece of evidence that has pointed to the need for an interference mechanism in the context of Hebb verbal sequence learning--the attenuation of learning with item-set overlap (Melton, 1967; Page et al., 2013)--reflects instead the *facilitative* effect of item-set learning when there is no item-set overlap, not the negative impact of interference from non-repeated sequences when there is complete item-set overlap. If so, what seems to be required to examine whether there is a need to invoke an interference mechanism to model the (pure) Hebb repetition effect is to manipulate the degree of overlap between repeated and non-repeated sequences at the *item-order* level in the context of complete item-set overlap. However, the present results already, indirectly, render it doubtful that interference at the item-order level plays a major role: With more non-repeated sequences between instances of the repeated sequence--e.g., 9 trials-apart *vs.* 4 trials-apart repetition-spacing--it was inevitably the case that there was more overlap at the item-order level between repeated and non-repeated sequences. And yet, the learning rate did not differ significantly between these two conditions. Thus, it remains unclear to us how the Page and Norris (2009) model could be modified without losing its essential character. With regard to the resilience of Hebb sequence learning to irregular repetition-spacing, the model has difficulty with this observation only to the extent that irregular spacing entails instances of wide repetition-spacing.

In summary, we have shown here that Hebb sequence learning is not modulated by repetition-spacing (at least up to 9 trials-apart spacing) and, for the first time, that this is the case with complete item-set overlap, contrary to received wisdom (e.g., Burgess & Hitch, 2006; Melton, 1963; Page & Norris, 2008, 2009; Page et al., 2013). A further novel demonstration was that pure Hebb sequence learning is also not affected by an irregularity of repetition-spacing, even when that would entail some instances of 16 trials between repetitions. The present data are hence a testament to the power of verbal sequence learning and are highly commensurate with the proposal that Hebb sequence learning constitutes a laboratory analogue of phonological word-form learning (e.g., Mosse & Jarrold, 2008; Page & Norris, 2008, 2009; Szmalec et al., 2009). Somewhat ironically, however, these same findings call for modifications--potentially major ones--to a model (Page & Norris, 2009) that was specifically built to relate Hebb sequence learning to phonological word-form learning. They are readily handled, however, by a more parsimonious version of the model of Burgess and Hitch (2006) in which its long-term decay component is simply discarded.

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Figure 1

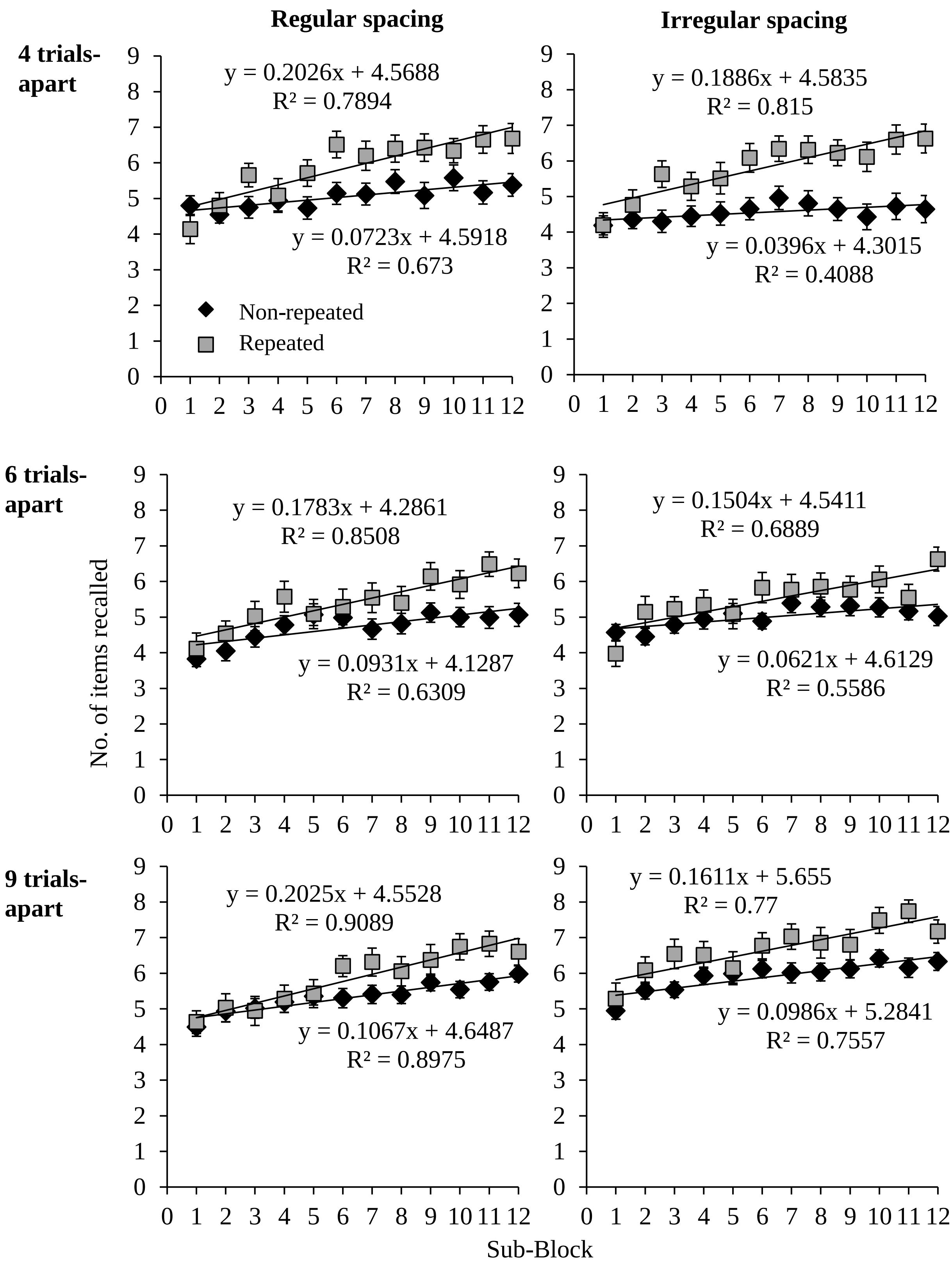
Regular spacing
Irregular spacing
4 trials-apart
6 trials-apart
9 trials-apart
y = 0.2026x + 4.5688
R² = 0.7894
y = 0.0723x + 4.5918
R² = 0.673
Non-repeated
Repeated
y = 0.1886x + 4.5835
R² = 0.815
y = 0.0396x + 4.3015
R² = 0.4088
y = 0.1783x + 4.2861
R² = 0.8508
y = 0.0931x + 4.1287
R² = 0.6309
y = 0.1504x + 4.5411
R² = 0.6889
y = 0.0621x + 4.6129
R² = 0.5586
y = 0.2025x + 4.5528
R² = 0.9089
y = 0.1067x + 4.6487
R² = 0.8975
y = 0.1611x + 5.655
R² = 0.77
y = 0.0986x + 5.2841
R² = 0.7557
No. of items recalled
Sub-Block

Figure Legends

Figure 1. Mean number of items recalled for the repeated and non-repeated sequences in each sub-block (recall performance was averaged for all non-repeated sequences within a sub-block) in the regular and irregular conditions within the 4 trials-apart, 6 trials-apart, and 9 trials-apart conditions. Regression lines were computed separately across repeated and non-repeated sequences and have been added to the plots. Error bars represent the standard error of the means.

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