The Articulatory Determinants of Verbal Sequence Learning

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RUNNING HEAD: Articulatory Determinants of Verbal Sequence Learning

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Abstract

Two experiments (*N* = 154 in total) using the Hebb repetition effect—the enhancement of serial recall performance for a repeated sequence in amongst otherwise non-repeated sequences—reveal a key role for active articulatory-planning processes in verbal sequence learning, contrary to a prominent, phonological-store based, model (Burgess & Hitch, 2006). First, Hebb sequence learning was attenuated when articulatory planning of the to-be-remembered sequence was restricted by articulatory suppression. This was less the case with auditory sequences, however, suggesting that passive perceptual organization processes operating independently of articulation also contribute to the learning of sequences presented auditorily. Second, sequence learning was enhanced for phonologically similar compared to dissimilar items when that learning was particularly reliant on articulatory planning (i.e., with visual sequences). That this enhanced learning was eliminated when articulatory planning was restricted also points to an articulatory basis for this 'phonological' similarity effect. Third, an inconsistent temporal grouping of items across instances of the repeating sequence also abolished learning but only when that grouping—based on independent evidence from output response-times during serial recall—was instantiated within an articulatory plan. These results are the first to suggest that verbal sequence learning, and not only verbal serial short-term memory performance, may be explicable by recourse to general-purpose articulatory and perceptual processes.

KEYWORDS: Verbal Sequence Learning; Hebb Effect; Articulatory Planning; Short-Term Memory.

Learning any skilled behavior involves the integration of individually-known elements into a new sequence (Melton, 1963). The ability to learn a new word, for example—a basic building-block of language acquisition—involves the unitization of a novel sequence of phonetic elements into a new long-term representation (Ellis, 1996). A well-established way in which such verbal sequence learning has been studied is through the Hebb repetition effect (e.g., Hebb, 1961; Melton, 1963; Mosse & Jarrold, 2008; St-Louis, Hughes, Saint-Aubin, & Tremblay, 2019). This paradigm involves a short-term serial recall task in which one sequence (e.g., 5-8 letters, digits, or words) is repeated several times (e.g., on every third trial) among otherwise novel, 'filler', sequences. Long-term verbal sequence learning is indicated by the enhanced serial recall of the repeating sequence compared to the filler sequences. There is now good evidence that the Hebb repetition effect constitutes a laboratory analog of natural word-form learning (e.g., Mosse & Jarrold, 2008; Szmalec et al., 2009, 2012; Yanaoka, Nakayama, Jarrold, & Saito, 2019). Indeed, given the great value of the Hebb effect for investigating the relation between short- and long-term serial memory, both in and outside the language domain (e.g., Couture & Tremblay, 2006), it has recently been identified as a "benchmark of high priority" for theories of short-term and working memory (Oberauer et al., 2018). Interest in the present article centres on the role of short-term subvocal-articulatory planning in Hebb verbal sequence learning. While such articulatory planning is given a key role in several theories of verbal serial recall and short-term/working memory (e.g., Baddeley, 1986, 2007; Barrouillet, Bernardin, & Camos, 2004; Hughes, Chamberland, Tremblay, & Jones, 2016; Jones, Macken, & Nicholls, 2004), it has been argued that it plays no role in Hebb verbal sequence learning (Burgess & Hitch, 2005, 2006; Hitch, Flude, & Burgess, 2009). Contrary to this position, we present evidence that active articulatory planning—together with an additional contribution of passive acoustic-perceptual processes with auditorily-presented sequences—is a key determinant of verbal sequence learning.

A commonly held view is that (sub)vocal-articulatory rehearsal or planning is a key process supporting the capacity to retain and reproduce a novel verbal sequence over the short term (e.g., Baddeley, 1986, 2007; Barrouillet et al., 2004; Hughes et al., 2016; Jones et al., 2004). The chief line of support for this comes from the finding that if the ability to engage in vocal-articulatory processing is restricted by requiring participants to engage in concurrent articulation of an irrelevant word or sequence (e.g., "x, y, z, x, y, z…")—so-called *articulatory suppression*—recall is impaired dramatically (Baddeley, 1986; Hughes & Marsh, 2017; Jones et al., 2004; Murray, 1968; but see also Lewandowsky & Oberauer, 2015). In one of the most prominent theories of verbal serial recall—the phonological loop model (Baddeley, 1986, 2007; Baddeley, Papagno, & Gathercole, 1998)—the function of articulatory processes is to support the retention of individual items in a dedicated short-term phonological store by counteracting a decay process, as well as to convert visually-presented items into a form suitable for the store. Of particular interest here is the claim that while articulatory processes support the short-term phonological storage of individual items, those processes are not involved directly in the short-term sequencing required for short-term serial recall nor in the long-term learning of a sequence (Burgess and Hitch, 2006; Hitch et al., 2009). In Burgess and colleagues' account, the sequential order of items is represented in the form of a positional context-signal that is independent of articulatory processes and of the phonological store that those processes support (for earlier instantiations of the model, see Burgess & Hitch, 1992, 1999). The linking up of item-information residing in the phonological store and the representation of item-order only occurs at a second stage of processing. Crucially, it is the initial phonologically-insensitive stage of encoding the order of items that supports verbal sequence learning such as that witnessed in the Hebb sequence learning task. This core assumption leads to the prediction that variables that are, on this model, assumed to impair short-term serial recall via their influence on phonological item-storage (rather than item-order) should not affect long-term verbal sequence learning. And indeed, the available evidence appears to support this position: First, it has been reported that while impeding articulatory planning via articulatory suppression has a major detrimental effect on short-term serial recall, it has no effect on Hebb sequence learning (Hitch et al., 2009; Page, Cumming, Norris, Hitch, & McNeil, 2006), consistent with the assumption that articulatory processes are involved in phonological item-storage but not in sequencing. The second line of evidence relates to what has commonly been considered the empirical hallmark of the phonological short-term store, the phonological similarity effect (e.g., Baddeley, 1986, 2007): While short-term serial recall of phonologically similar items (e.g., *B, D, T…*) is much poorer than phonologically dissimilar items (e.g., *H, K, L…*), such similarity again does not modulate Hebb sequence learning (Hitch et al., 2009).

At the core of Burgess and colleagues' account of verbal serial short-term memory and sequence learning is the assumption that articulatory suppression and phonological similarity exert their effects on a passive short-term phonological store that is separate from articulatory processes. However, in recent years, the primary empirical basis for postulating the existence of such a store has been challenged (Jones et al., 2006, 2004, 2007; Maidment & Macken, 2012). The key piece of evidence for a phonological store independent of articulatory processes is a three-way interaction between phonological similarity, articulatory suppression and presentation-modality: With visual presentation, the putative signature of the store, the phonological similarity effect, disappears when articulatory processes are restricted by articulatory suppression. The argument is that under suppression, visual-verbal items cannot be converted into phonological form and hence do not access the store. However, the phonological similarity effect is still evident despite articulatory suppression if presentation is auditory because auditory-verbal items are already in phonological form and hence enjoy automatic access to the phonological store. As such, the hallmark of the action of the phonological store is evident despite the incapacitation of articulatory processes. The logical conclusion is that there must, therefore, be a passive phonological store independent of articulatory processes (Baddeley, Lewis, & Vallar, 1984; Baddeley & Larsen, 2007).

A number of studies have now shown, however, that the character of the critical interaction just described does not take the form initially, and typically still, assumed. It transpires that articulatory rehearsal is indeed a precondition for the phonological similarity effect regardless of modality: The effect is eliminated by articulatory suppression even with auditory presentation throughout most of the serial position curve (Jones et al., 2004). The survival of the effect under suppression is restricted primarily to recency and hence driven by the modality effect, the advantage for the recall of the last one or two items of an auditorily-presented compared to a visually-presented sequence (also known as auditory recency; Conrad & Hull, 1968). Thus, it is the fact that the modality effect survives articulatory suppression that accounts for the survival of the phonological similarity effect under suppression with auditory sequences (Jones et al., 2004, 2006; Watkins et al., 1974)[1]. Crucial to the re-evaluation of the critical three-way interaction is that the modality effect is generally regarded as the product of acoustic, not phonological, factors (for a review, see Nicholls & Jones, 2002a); indeed, as a result, the modality effect is considered to be "peripheral to the working memory system" (Baddeley, 1986, p. 95; see also Hurlstone, Hitch, & Baddeley, 2014). Thus, notwithstanding the residual acoustic-based 'phonological' similarity effect at recency under suppression with auditory presentation, engagement in vocal-articulatory

[1] It is worth pointing out that the elimination of the phonological similarity effect under suppression in these studies cannot simply be attributed to a floor/proportional scaling effect (cf. Beaman, Neath, & Surprenant, 2008; Wang, Logie, & Jarrold, 2016): The elimination of the phonological similarity effect by articulatory suppression can be observed at the same level of general recall performance at which, in other conditions or experiments, the similarity effect is clearly present (e.g., Jones et al., 2006; Maidment & Macken, 2012).

processes is a prerequisite for the phonological similarity effect regardless of modality. As such, it has been argued that the locus of the phonological similarity effect is not a passive phonological store but an articulatory planning process (Jones et al., 2006, 2004). Specifically, in this view, the reproduction of a phonologically similar sequence in a serial recall task is relatively poor because the articulatory planning of such a sequence is particularly prone to errors. Indeed, the nature of the item-order errors found in serial recall of phonologically similar lists mimics very closely the kind of speech errors that are produced occasionally during normal phrase or sentence production (Acheson & MacDonald, 2009; Ellis, 1980; Page, Madge, Cumming, & Norris, 2007). For example, natural speech-planning errors in which two consonants swap places are more likely if the syllables of which they are a part share a similar or identical vowel, a phenomenon dubbed the contextual similarity effect (Ellis, 1980; e.g., the swapping of the *l* and *f* when intending to say "*l*ight a *f*ire" but mistakenly uttering "*f*ight a *l*iar"; MacKay, 1970; Nooteboom, 1967). The typical phonologically similar list used in serial recall tasks (e.g., *B, D, T…*) is an extreme example of a sequence exhibiting contextual similarity: The 'syllables' all have consonant-onsets that share an identical vowel (which also acts as the coda in each syllable), making the erroneous swapping of consonants (to produce, for example, *D, B, T*…) particularly likely.

The evidence undermining the notion of a phonological short-term store fractionated from vocal-articulatory processes has led to the view that serial short-term memory performance generally can be conceptualized more parsimoniously as being parasitic on articulatory planning (regardless of presentation-modality; Wolpert, Ghahramani, & Flanagan, 2001) and processes involved in the perceptual organization of acoustic input (when material is presented auditorily; Bregman, 1990; Oxenham, 2018; Hughes & Marsh, 2017; Hughes. Marsh, & Jones, 2009, 2011; Hughes et al., 2016; Jones et al., 2006, 2004; Macken et al., 2016). On this perceptual-motor account, articulatory planning, rather than counteracting the negative effect of item-decay in a separate store (cf. Baddeley, 1986, 2007), plays the constructive role of sequentially binding the list items which are, by design, grammatically and semantically unrelated (e.g., Hughes et al., 2016; Jones et al., 2004; Macken, Taylor, & Jones, 2015). That is, the articulatory plan itself serves as the main substrate of short-term sequence retention and reproduction. As such, both phonological similarity and articulatory suppression in this view directly affect the articulatory planning process supporting the reproduction of the sequence rather than affecting, respectively, the retrieval of items from a passive (i.e., non-articulatory) phonological store and a process designed to offset their decay as in the phonological-store account. Our view that articulatory sequencing processes are the basis of verbal serial recall performance (other than when perceptual organization processes can also contribute to performance with auditory lists) leads us to our present hypothesis that the long-term learning of a (repeating) sequence largely reflects the long-term legacy of that same articulatory sequencing process. This hypothesis is already lent some credence by the success of general models of motor-skill learning in which such learning grows out of short-term motor control (Willingham, 1998). In the present study, we provide several convergent tests of the hypothesis as well as examine the possible contribution of passive perceptual organisation processes when verbal sequences are presented auditorily.

Experiment 1

In Experiment 1, we examine Hebb verbal sequence learning for the first time in the context of the intricate interplay of factors—phonological similarity, articulatory suppression, and presentation modality—that has been instrumental in demonstrating a primary role for articulatory-sequence planning in verbal serial recall (e.g., Jones et al., 2006, 2004). By examining the impact of these interacting factors on short-term serial recall and, simultaneously, on the enhancement of the serial recall of a repeating Hebb sequence, we aim to reveal the contributions of articulatory planning as well as auditory perceptual organization (with auditory sequences) to long-term verbal sequence learning. Our first prediction was that if articulatory planning plays an important role in verbal sequence learning, articulatory suppression should reduce the Hebb effect. Whilst this prediction may seem to have already been disconfirmed, scrutiny of the relevant past studies suggests this conclusion may have been premature. First, in Experiments 1 and 2 of Hitch et al. (2009), unusually long lists of 12 items were used, a list-length at which an articulatory-planning based strategy (and indeed a phonological-store based one; cf. Baddeley & Larsen, 2007) may be unlikely to be adopted. Second, only auditory presentation was used in those experiments; from the standpoint of the perceptual-motor approach, auditory presentation reduces the likelihood of detecting an effect of suppression due to the expected contribution to auditory-verbal sequence learning of passive acoustic-based perceptual organisation processes that operate independently of articulatory processes (Jones et al., 2004). Indeed, in Experiment 3 of Hitch et al. (2009), in which shorter, 8-item, lists were presented visually, there was indeed some evidence of an attenuation of Hebb sequence learning under suppression: The authors reported that there was an interaction between list-type (Hebb-phonologically-dissimilar, Hebb-phonologically-similar, Filler) and suppression but attributed this solely to an attenuation of the phonological similarity effect in serial recall (and hence not to do with sequence learning). However, scrutiny of their data suggests that this interaction may have been attributable also to an attenuating effect of suppression on the difference between filler and Hebb sequences, that is, an effect of suppression on the Hebb effect. Third, all three experiments in Hitch et al. (2009) involved steady-state suppression (i.e., “the, the, the…”), a procedure known to be a less effective means of restricting articulatory planning than changing-state suppression (e.g., “x, y, z…” or “eight, nine, ten…”; Macken & Jones, 1995). Fourth, in Experiment 3 of Hitch et al. (2009), the filler sequences did not comprise the exact same set of items as the repeating

Hebb sequence, contrary to the standard procedure. As such, the repetition effect may in part have reflected the learning of which items were a part of the repeating set (i.e., item-set learning) rather than sequence learning per se. The same ‘item-set learning’ issue, as well as the use of steady-state, as opposed to changing-state, suppression applies to the only other report of an absence of a suppression effect on Hebb verbal sequence learning (Page et al., 2006, Experiment 1). In the present experiments, therefore, we used relatively short lists (7 items), included both visually and auditorily presented sequences, required changing-state articulatory suppression (compared to no suppression), and had full item-set overlap between filler and Hebb sequences.

The second way in which we examined the role of articulatory planning in Experiment 1 was through a manipulation of phonological similarity as well as through the interaction of phonological similarity with articulatory suppression and modality. Given the evidence that the phonological similarity effect is, notwithstanding the acoustic-based effect at recency, the product of articulatory-planning errors (Acheson & MacDonald, 2009; Jones et al., 2004; Page et al., 2007), a role for articulatory planning in verbal sequence learning may also be revealed in the form of a modulation of such learning by phonological similarity. The claim that Hebb sequence learning is not modulated by phonological similarity currently rests on the results of a single experiment: Hitch et al. (2009, Experiment 3) tested and seemed to confirm the “counterintuitive prediction that phonemic similarity should not impair sequence learning, despite having its normal effect of disrupting STM [short-term memory] for serial order” (p. 106). Again, however, interpretation of that experiment is complicated by the possibility that the learning effect observed was at least partly an item-set learning effect. Furthermore, it is noteworthy that the only hypothesis entertained in previous work is that phonological similarity may *impair* sequence learning (Hitch et al., 2009), presumably on the grounds that it impairs short-term serial recall. But this is not the only possible—or indeed necessarily most plausible—hypothesis. On an articulatory-planning based account, there are good reasons to expect a greater learning effect for phonologically similar compared to dissimilar sequences; that is, the recall of phonologically similar sequences may benefit more from repeated opportunities to plan that sequence than is the case for a phonologically dissimilar sequence. The more error-prone a motor-skill is to begin with, the more that skill stands to benefit from practice (e.g., Heathcote, Brown, & Mewhort, 2000; Newell & Rosenbloom, 1981). In addition, we predicted that if any enhanced learning effect found with a phonologically similar sequence is indeed located in the articulatory-planning process, it should be attenuated or eliminated under articulatory suppression, at least with visual sequences in which passive auditory perceptual organization could not support any learning.

As well as investigating the role of articulatory planning in verbal sequence learning, we were also interested in this experiment in the possible additional contribution of passive auditory perceptual organization processes to the learning of an auditorily presented sequence. Such a contribution should be evident in differences in the Hebb repetition effect according to the modality of presentation (i.e., auditory as opposed to visual), at least under articulatory suppression when the contribution of articulatory planning—common to both modalities—would be reduced. Specifically, we predict that although learning should still be diminished with auditory sequences when articulatory planning is restricted by articulatory suppression, this diminution should not be as marked with auditory sequences because of the independent contribution to auditory sequence learning of passive acoustic-based perceptual organization processes that by-pass articulatory planning processes (Jones et al., 2004).

In sum, then, in this experiment participants were required to serially recall sequences of seven letter-names that were either phonologically similar or dissimilar to one another and to do so while being free to engage in articulatory planning or whilst engaging in articulatory suppression. Moreover, the sequences were presented either visually or auditorily.

Method

Both experiments reported in the present article were granted ethical approval by the Ethics committee of Royal Holloway, University of London.

Participants. To determine an appropriate sample size, we first identified that the Hebb effect tends to have a medium effect-size (estimated Cohen's *d* ranging between ~ .4 and ~ .7; Bogaerts et al., 2015; Hitch et al., 2009; Page et al., 2006). Given the relatively large number of factors in our experiment and the fact we were interested in interactions among them, we wanted a sample size that would allow for the potential detection of a small- to medium-sized effect (e.g., Cohen's *d* ~ .3) with a relatively large amount of power. We calculated that a sample size of 52 would allow this with a power of .9. We therefore ran 52 participants for the present experiment and 52 for each of the two between-participants groups in Experiment 2. The participants in Experiment 1, then, consisted of six males and 46 females, all students at Royal Holloway, University of London (mean age: 19.17 years, SD = 1.63). They received either course credits or a small honorarium for their participation.

Apparatus and materials. The experiment was conducted using E-Prime software (Psychology Software Tools, Pittsburgh, PA) running on a PC. The visual stimuli were presented on a flat monitor and the auditory stimuli via headphones. For the with-suppression condition, a microphone was used for on-line monitoring of each participant's compliance with the whispered articulatory suppression instruction (see below). The to-be-remembered sequences consisted of a random ordering of either the phonologically similar letters *B, C, D, G, P, T,* and *V,* or the phonologically dissimilar letters *F, H, K, L, Q, R,* and *Y* and these could be presented either visually or auditorily. Regardless of input-modality, the letters were presented for 250 ms with an inter-stimulus-interval of 750 ms. The auditorily presented letters were recorded in a female voice at a pitch corresponding to a fundamental frequency of approximately 210 Hz, sampled with a 16-bit resolution at a rate of 48 kHz, and compressed to 250 ms (without altering pitch) with Sonic Forge 5.0 software (Sonic Foundry, Inc., Madison, WI; 2000). The visually-presented letters were presented in a 72-point Times Roman font in the centre of the monitor.

Design. The experiment involved five repeated-measures factors in all: Modality (visual, auditory), Articulatory suppression (no-suppression, with-suppression), Phonological similarity (similar, dissimilar), List-type (Hebb, Filler), and Cycle (referring to each successive triplet of trials across a block, comprising a Hebb sequence and two preceding filler trials). There were eight blocks of serial recall trials in total, each consisting of 36 sequences of seven letters where every third sequence (starting with trial 3) was the same, repeating, Hebb sequence, amounting to 12 instances of the Hebb sequence within a given block. The experiment was divided into two order-counterbalanced blocks according to Modality and these were undertaken on different days. Each modality block/session was itself sub-divided into four 36-trial blocks; two of these blocks comprised all phonologically-similar sequences and two comprised all phonologically-dissimilar sequences. Finally, in one block in each phonological similarity condition (i.e., similar and dissimilar), participants engaged in changing-state articulatory suppression (with-suppression blocks) whilst in the other block in each phonological similarity condition they did not (no-suppression blocks). The four blocks [2(Phonological similarity) × 2(Articulatory suppression)] within each modality were presented so that phonologically similar and dissimilar trial-blocks alternated. Specifically, there were four possible block-orders: A1-B2-A2-B1, A2-B1-A1-B2, B1-A2-B2-A1 or B2-A1-B1-A2, where A = similar, B = dissimilar, 1 = no-suppression, and 2 = with-suppression. For each of the eight blocks, the participant undertook one of two possible counterbalanced sets of trials (unique to each block) which differed in terms of the order of items within both the Hebb sequence and the filler sequences.

Procedure. The experiment was divided into two sessions held between 1 and 14 days apart, with a randomly assigned half of the participants completing the four visual blocks in the first session followed by the four auditory blocks in the second and vice versa for the other half of participants. Participants were tested individually and wore the headphones throughout both sessions (except when receiving oral instructions from the Experimenter). At the beginning of the first session, participants gave informed consent and were then given task instructions. These included a description of the immediate serial recall task, the four-block structure of the session and the articulatory suppression that would be required in a sub-set of the blocks. The articulatory suppression involved repeatedly whispering ‘eight, nine, ten…’ at a rate of approximately three items per s during both the presentation of the letters and during the recall attempt (note that the recall mode was manual; see below). The Experimenter demonstrated the approximate (whispered) form and rate of articulatory suppression and participants then practiced the suppression before any serial recall trials. With the permission of the participant, compliance with these articulatory suppression instructions was monitored ‘live’ by the Experimenter throughout the experimental trials through an audio link. Before each block, the participants were instructed on whether or not they had to undertake articulatory suppression and received two practice trials that corresponded to the nature of the trials in the upcoming block. In the experiment, each presented sequence was followed by an immediate serial recall cue in which the participants clicked the letters from a circular array presented on the monitor in the order they saw/heard them. Importantly, the order of the letters in the circular response array was randomized anew for each trial, including the Hebb trials. This means that learning the repeating sequence could not be based on a repeating spatial sequence of clicks or on the planning or production of a repeating sequence of finger-movements (cf. Fendrich, Healy, & Bourne, 1991; Page et al., 2006). After recall, participants moved to the next sequence by clicking an icon to start the new sequence. Neither the particular phonological similarity condition nor the Hebb repetition manipulation was mentioned to participants at any point until the debriefing following the last block of the second session. Each of the two sessions lasted approximately one hour.

Results

Due to a technical issue, the data from two participants could not be used, thus the following analyses were based on the data from 50 participants.

Serial recall. We first examined serial recall performance per se (as opposed to Hebb sequence learning). The data for this analysis were, for each of the eight [2(Phonological similarity) × 2(Modality) × 2(Articulatory suppression)] blocks, those from the 24 filler trials and the first instance of the Hebb sequence (which in effect was equivalent to a filler sequence as it would not have been presented previously at that point). For each sequence, an item was scored as correct only when recalled in the same absolute position as that in which it was presented.

Figure 1 shows the percentage of items recalled correctly at each serial position in each of the eight conditions. In the absence of articulatory suppression (left panel), a clear phonological similarity effect is evident for both visual and auditory sequences. Under suppression (right panel), however, the phonological similarity effect is eliminated with visual sequences but remains with auditory sequences. Importantly, however, replicating previous studies (Jones et al., 2004; Maidment & Macken, 2012), this survival of the phonological similarity effect with auditory presentation under suppression is located primarily at recency.

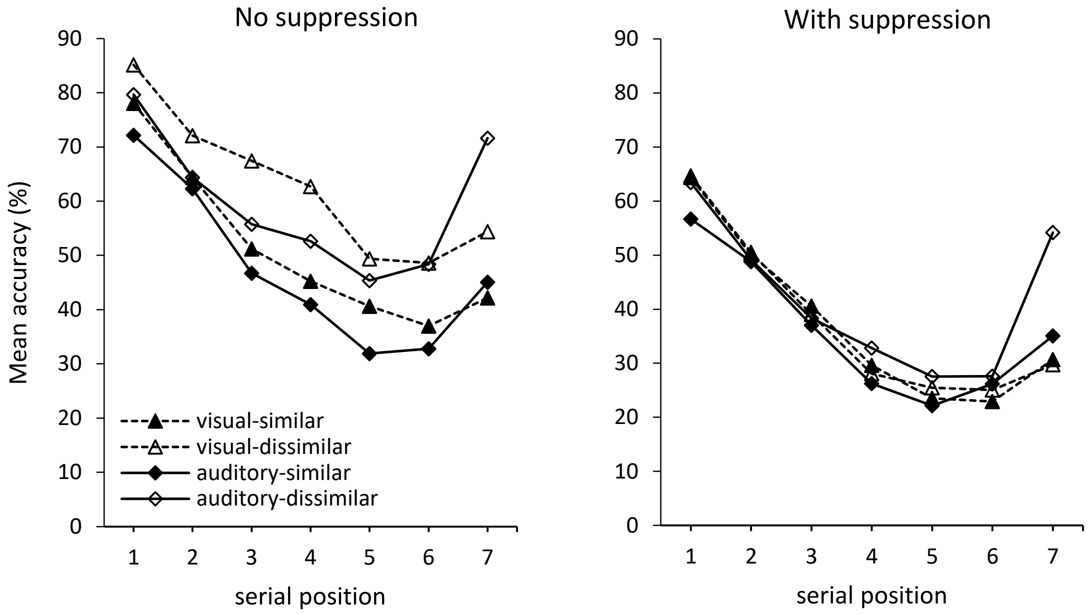

Figure 1. Accuracy of serial recall performance on filler lists only in the eight conditions of Experiment 1 according to serial position.

In line with this impression of the data, a 2 (Modality) × 2 (Phonological similarity) × 2 (Articulatory suppression) × 7 (Serial position) repeated measures ANOVA showed main effects of Phonological similarity, $F(1, 49) = 42.9$, $MSE = .09$, $p < .001$, $\eta_p^2 = .47$, Articulatory suppression, $F(1, 49) = 176.12$, $MSE = .12$, $p < .001$, $\eta_p^{\ 2} = .78$, and Serial position, $F(6, 294) = 231.18$, $MSE = .03$, $p < .001$, $\eta_p^{\ 2} = .83$. No significant main effect of Modality was observed, $F(1, 49) = 1.20$, $MSE = .07$, $p = .28$, $\eta_p^{\ 2} = .02$. Importantly, however, a significant four-way interaction was found, $F(6, 294) = 3.13$, $MSE = .01$, $p = .005$, $\eta_p^{\ 2} = .06$, in line with our observation based on Figure 1: While the phonological similarity effect survived suppression only with auditory sequences, this was primarily the case at recency. (For completeness, other significant interactions subsumed within this four-way interaction are included in Table A1 in the Appendix, which provides the full set of results from the analyses of Experiment 1.)

Thus, the pattern of serial recall performance replicates closely that which has formed the empirical basis of the argument that such performance can be explained by recourse to articulatory planning processes and auditory perceptual organization (e.g., Jones et al., 2006, 2007; Macken et al., 2016; Maidment & Macken, 2012). As such, the serial recall data provide a suitable platform from which we can now examine the role that these same processes may play in the long-term learning of a verbal sequence.

Hebb sequence learning. The analysis of Hebb sequence learning involved, for each of the eight [2(Phonological similarity) × 2(Modality) × 2(Articulatory suppression)] blocks/conditions, the serial recall data from the twelve Hebb sequences and the average recall of each pair of filler sequences that preceded each instance of the Hebb sequence (hereafter: 'fillers'). For the purpose of this analysis, performance accuracy for each list was collapsed over serial positions. These data, shown in Figure 2, were entered into a 2 (List-type: Hebb vs. Filler) by 2 (Modality) by 2 (Phonological similarity) by 2 (Articulatory suppression) by 12 (Cycle) repeated measures ANOVA. First, this analysis revealed several main effects that we do not report here in detail—those of Phonological similarity, Articulatory suppression and Modality—because these reflect the same effects as already reported in the previous sub-section on serial recall performance per se (rather than pertaining specifically to sequence *learning*). Turning now to effects that are indeed relevant to the assessment of Hebb sequence learning, the main effect of List-type was significant, $F(1, 49) = 59.25$, $MSE = .19$, $p < .001$, $\eta_p^2 = .547$, reflecting the better recall of Hebb sequences compared to the fillers (i.e., the classic Hebb effect), as was the List-type by Cycle interaction, $F(11, 539) = 7.64$, $MSE = .04$, $p < .001$, $\eta_p^2 = .135$, which likely reflects, primarily, the fact that the benefit of repetition increases as a function of the number of repetitions (i.e., that Hebb sequence learning is progressive, at least across eleven repetitions of the Hebb sequence as was the case in the present experiment)[2]. The main effect of Cycle

[2] Following Oberauer, Jones, and Lewandowsky (2015), we take a main effect of List-type as being just as indicative of Hebb sequence learning as an interaction between List-type and Cycle or a steeper slope for the Hebb compared to Filler condition (e.g., Page et al., 2006). This is because only

was also significant, $F(7, 389.8) = 9.48$, $MSE = .06$, $p < .001$, $\eta_p{}^2 = .162$, which also likely reflects the increasingly beneficial effect of Hebb repetition across a block.

There were several reliable interactions that, like some of the reliable main effects, reflect patterns in the serial recall data per se that we have already reported and that do not relate to the Hebb effect (the full set of results is, however, reported in Table A2 in the Appendix). However, there were also several significant interactions that do indeed reflect a modulation of Hebb sequence learning by one or more of the other factors: Of particular interest was a reliable interaction between List-type and Articulatory suppression, $F(1, 49) = 7.8$, $MSE = .15$, $p = .007$, $\eta_p{}^2 = .14$, whereby the Hebb effect was attenuated under articulatory suppression. In addition, while the List-type by Phonological similarity interaction was not significant, this was because these two factors entered into a reliable three-way interaction with Modality, $F(1, 49) = 5.06$, $MSE = .15$, $p = .029$, $\eta_p{}^2 = .09$, as well as a reliable four-way interaction with Modality and Articulatory suppression, $F(1, 49) = 4.6$, $MSE = .06$, $p = .037$, $\eta_p{}^2 = .086$. To aid in the interpretation of this complex interaction, we supplement Figure 2 with Table 1, which shows the results of the critical Hebb *vs*. Filler pairwise contrast as a function of Modality, Similarity, and Suppression[3].

Inspection of Figure 2 and Table 1 suggests that the reliable four-way interaction reflects the following pattern of effects: With visual sequences (cf. Panels A and B of Figure 2), and in the absence of articulatory suppression, there was a Hebb effect with both phonologically dissimilar sequences (Panel A) and similar sequences (Panel B). However,

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Hebb sequence learning could account for a difference in performance due to list-type and, moreover, an interaction between list-type and cycle or a difference in slopes could be absent despite a clear Hebb effect (as indicated by a main effect of list-type), due, for example, to very rapid learning.

[3] It has been reported that participants tend to make the same recall errors repeatedly in response to the repeating sequence and that this can sometimes obscure a 'true' sequence learning effect (Lafond, Tremblay, & Parmentier, 2010). However, an analysis of response-error learning conducted following the protocol of Lafond et al. (2010) found little evidence of this in the present experiment; a given response error was generally not repeated more than once across a 12-cycle block.

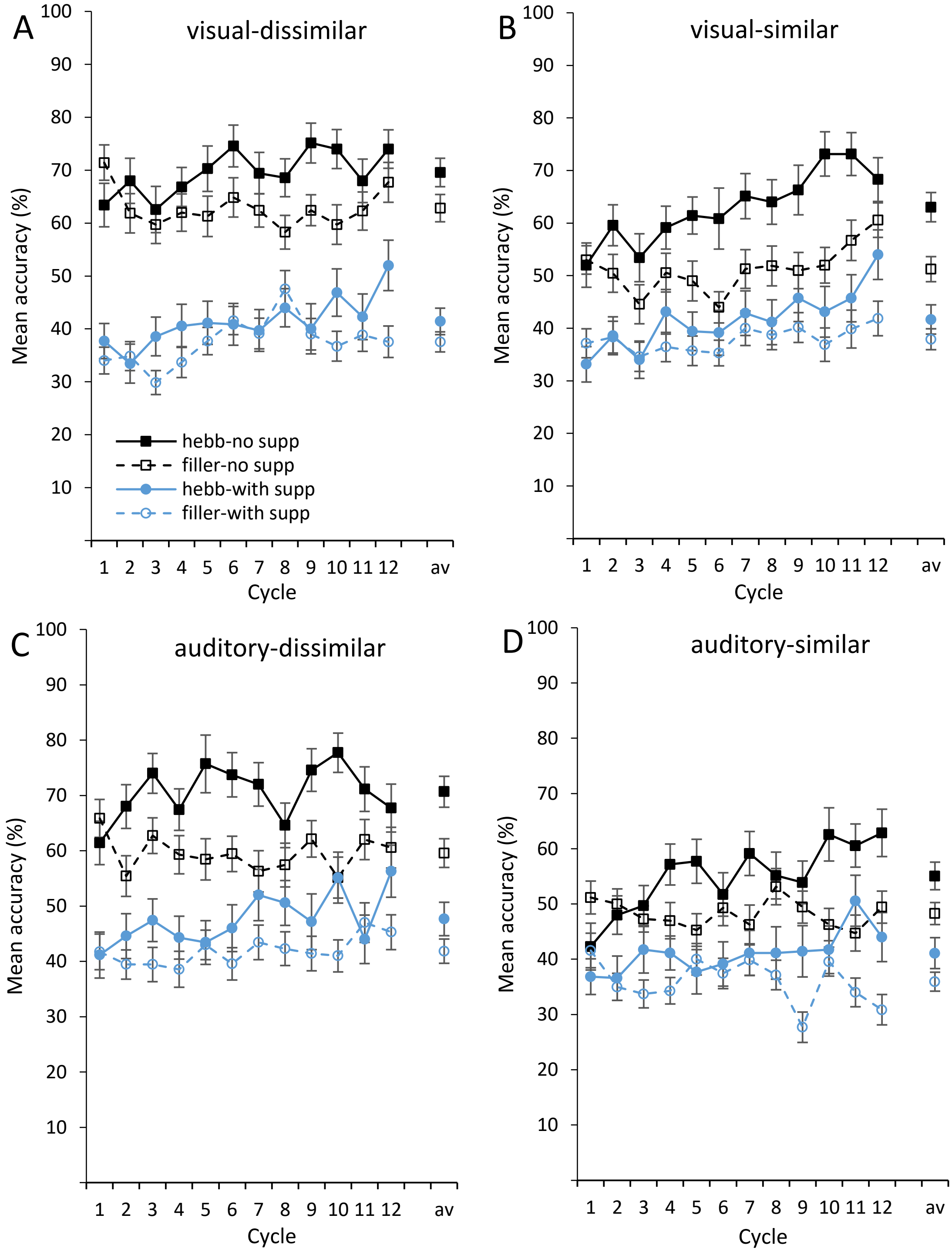

Figure 2. Serial recall accuracy (collapsed across serial position) at each Cycle according to List-type, Suppression, Modality, and Phonological similarity in Experiment 1.

Modality	Similarity	Suppression	Hebb (%)	Filler (%)	Magnitude of the Hebb effect (Hebb – Filler) (%)	*p*
Visual	Dissimilar	No-supp	69.9	62.8	7.1	.003
		With-supp	41.4	37.5	3.9	.023
	Similar	No-supp	63	51.2	11.8	<.001
		With-supp	41.7	37.9	3.8	.038
Auditory	Dissimilar	No-supp	70.7	59.6	11.1	.019
		With-supp	47.7	41.8	5.9	.024
	Similar	No-supp	55.1	48.3	6.8	.021
		With-supp	41.1	35.9	5.2	.018

Table 1. Hebb vs. Filler pairwise comparisons according to Modality, Phonological similarity, and Articulatory suppression (supp).

regardless of similarity, the Hebb effect was clearly attenuated by articulatory suppression. Also evident with visual presentation was a modulation of the Hebb effect by phonological similarity: Without suppression, the Hebb effect was *larger* for phonologically similar than dissimilar sequences (compare panel B with A), a difference no longer apparent under suppression. The pattern was different in a number of ways with auditorily presented sequences however (cf. Panels C and D of Figure 2): In the absence of articulatory suppression there was again a Hebb effect with both phonologically dissimilar and similar sequences but now the magnitude of the effect was greater for phonologically dissimilar than similar sequences. Moreover, the impact of articulatory suppression on the Hebb effect with auditory sequences was weaker than with visual sequences.[4]

[4] Given that there is only a single data-point for each participant for each instance of the Hebb list in each condition, it may be suggested that an ANOVA is not a suitable method. However, note that only in relation to the 5-way interaction would the measurement of performance in the Hebb condition have relied on a single data-point per participant per cycle and this interaction was not, in any case, reliable. Nevertheless, a linear mixed-effects analysis that avoids this issue leads to the same conclusions: An interaction model incorporating all terms of interest from the ANOVA, including the 4-way interaction (List-type, List-type × Cycle, List-type × Suppression, List-type × Similarity × Suppression, and List-type × Modality × Similarity × Suppression) was a better fit to the data than a model that did not include the interaction terms, $\chi^2(12) = 229.2$, $p < .001$.

Discussion

The results of Experiment 1 are in line with the view that Hebb verbal sequence learning is supported by articulatory planning and at the same time disconfirm basic predictions of Burgess and colleagues' account. Critical to our aims in relation to verbal sequence learning was our replication of the intricate pattern of short-term serial recall data (i.e., ignoring the Hebb repetition manipulation) that has challenged the main empirical basis of the phonological store construct (Jones et al., 2006, 2004; Maidment & Macken, 2012). Specifically, the survival of the phonological similarity effect under articulatory suppression with auditory presentation—an observation that has been pivotal to the notion of a passive phonological store separable from articulatory rehearsal (Baddeley et al., 1984; Hitch et al., 2009)—is located primarily at recency, a portion of the serial recall curve considered to lie outside the remit of the phonological store (Baddeley, 1986; Hurlstone et al., 2014). The present data therefore reinforce the view that this vestige of the phonological similarity effect under suppression is an acoustic similarity effect, reflecting the contribution of passive, acoustic-based, perceptual organization factors to serial recall performance (Nicholls & Jones, 2002a). Thus, aside from this perceptual-acoustic effect, the apparent empirical signature of the passive phonological store—the 'phonological' similarity effect—is an articulatory similarity effect; a product of articulatory planning errors (Acheson & MacDonald, 2009; Jones et al., 2006, 2004).

The analysis of the Hebb effect provided several converging lines of evidence for our hypothesis that articulatory planning plays a key role not only in short-term verbal serial recall but also long-term verbal sequence learning. Using a more standard version of the Hebb paradigm than previous relevant studies (Hitch et al., 2009; Page et al., 2006), we found that restricting articulatory planning (through changing-state articulatory suppression) impaired Hebb sequence learning, especially with visual presentation in which such learning would be expected to be driven mainly by articulatory planning, that is, where passive auditory organization processes could not contribute. This result, which we go on to replicate in Experiment 2, contradicts the account of Burgess and colleagues (Burgess & Hitch, 2006; Hitch et al., 2009), which predicts that articulatory suppression should not affect Hebb sequence learning on the grounds that suppression disrupts phonological item-memory but not the stage of processing (order processing) assumed to underpin verbal sequence learning (Burgess & Hitch, 2006; Hitch et al., 2009).

One might ask, however, whether the attenuation of the Hebb effect under articulatory suppression in the present experiment was due to a proportional scaling effect (cf. Wang et al., 2016) whereby an effect (here Hebb learning) becomes less likely to be empirically detectable the lower the general level of performance (due in this case to the highly disruptive effect of articulatory suppression on serial recall, cf. Figure 1). However, this argument would be difficult to sustain. First, the Hebb effect under articulatory suppression was still marked with auditory presentation (as predicted by the perceptual-motor account; see below) despite a comparably poor overall level of performance (with recall of filler lists at 38.9 %) to that in the visual-with-suppression condition (37.7%). Second, the Hebb effect was sometimes larger at lower overall levels of performance (e.g., that found with visually-presented phonologically similar lists) than it was at higher overall levels of performance (that for visually-presented phonologically dissimilar lists). Both these observations suggest that, in the present data at least, there was not a clear association between overall levels of performance and the magnitude of the key effect of interest.

A second result that supports a role for articulatory planning in Hebb sequence learning was that learning was modulated by phonological similarity. The account of Burgess and colleagues predicts no such modulation because the order-representation stage that drives sequence learning is insensitive to the phonological identity of the items being ordered. The only previous study to have examined the possible effect of phonological similarity on Hebb sequence learning (Hitch et al., 2009, Experiment 3) found no phonological similarity effect using visual sequences (they did not include an auditory condition). But again, this result is difficult to interpret due to the possible contribution of item-set learning to the 'Hebb effect' in that experiment. From an articulatory planning standpoint, however, our finding that the greater learning of phonologically similar compared to dissimilar sequences with visual presentation—in which the role of articulatory planning should be evident in relatively pure form—is readily explicable via the notion that a relatively disfluent, error-prone, motor activity would stand more to gain from opportunities to re-plan the same sequence (cf. Heathcote et al., 2000). It is worth noting also that this enhanced effect cannot be ascribed simply to recall being at a relatively low level before learning commenced (i.e., at Cycle 1) and hence to there being more 'room' for learning to manifest empirically: Performance started at an even lower level under articulatory suppression and yet, as we have seen, learning was attenuated, not enhanced, under suppression, at least with visual sequences. Further reinforcing an articulatory locus for the enhanced learning of (visually-presented) phonologically similar sequences, the enhancement was not evident when articulatory planning was restricted by articulatory suppression.

Turning to our secondary interest in the possible contribution of passive auditory perceptual organization processes to Hebb sequence learning, we suggest that there was evidence for this in the observation that the Hebb effect remained relatively strong with auditory sequences despite articulatory suppression (compared to the case with visual sequences). Another possible signature of a contribution of auditory perceptual organization is that, in contrast to the case with visual sequences, the Hebb effect was stronger with phonologically dissimilar than similar sequences. This may be explicable by reference to the fact that passive processing of order in an auditory sequence is a positive function of the acoustic distinctiveness of its successive elements (so long as that distinctiveness is carried on a common ground such as a common voice; Bregman & Rudnicky, 1975; Hughes et al., 2009; Jones & Macken, 1995). This may have overridden the stronger, articulatory-based, learning effect otherwise found with a (visually-presented) phonologically-similar sequence. A future test of this interpretation could involve reducing the rate of presentation so as to weaken the influence of automatic auditory order processing (cf. Bregman, 1990) while leaving the influence of articulatory planning relatively unaffected.

The results of Experiment 1 are consistent with the suggestion that a key part of what underpins Hebb sequence learning is the increasing fluency of the articulatory plan generated to support the short-term recall of the Hebb sequence. The rationale for our next experiment is based on the notion that an articulatory plan embodies not only the sequence-items but also a particular prosodic organization of those items (e.g., Levelt, 1989). Indeed, we have argued previously that it is such paralinguistic features of articulatory planning that act as the scaffolding that binds the otherwise unrelated items together (Hughes et al., 2016; Jones et al, 2004; Macken et al., 2016). In Experiment 2, therefore, we test the prediction that changes in the temporal grouping within the articulatory plan across repetitions of the Hebb sequence—at least when the contribution to learning of auditory perceptual organization can be ruled out (i.e., with visual sequences)—should attenuate Hebb sequence learning.

Experiment 2

There is evidence that presenting a sequence of verbal items in two or more temporally-defined sub-groups for serial recall (e.g., *F*, *H*, *K*, *L*----*Q*, *R*, *Y*; where the dashed line represents a temporal gap between the *L* and *Q* that is longer than that between any other pair of successive items) invokes the (qualitatively) equivalent psychological grouping of the sequence. For example, the serial position function with such grouped lists is characterized by two or more (depending on the number of sub-groups) micro serial position curves, suggesting that the sequence is represented, at least to some extent, as separate sub-sequences (e.g., Frankish, 1985, 1989; Hitch, Burgess, Towse, & Culpin, 1996; Ryan, 1969). The finding that this modulation of the serial position function is attenuated under articulatory suppression (Hitch et al., 1996) suggests further that the internal grouping is, at least in part, instantiated within an articulatory plan. Furthermore, it has been found that the timing of responses when serially recalling a grouped sequence qualitatively mimics the presented grouping (Maybery, Parmentier, & Jones, 2002). We capitalize on grouping effects in serial recall here to provide convergent evidence on the role of articulatory planning in Hebb sequence learning.

It has already been reported that presenting the Hebb sequence with different temporal groupings across repetitions attenuates the Hebb effect (Hitch et al., 2009, Experiment 2; see also Bower and Winzenz, 1969). However, in contrast to our suggestion, Hitch et al. (2009) argued that temporal grouping-inconsistency affects an abstract representation of the positions of the items that is independent of articulatory processes. That is, in their phonological-store based model, timing is not represented in the phonological store (where effects of articulatory processes reside) but within a separate context-timing signal that represents order/positional information (Burgess & Hitch, 2006). This led Hitch et al. (2009) to predict that: i) inconsistent grouping should impair the Hebb effect (because such grouping disrupts the timing signal); and ii) articulatory suppression—which is thought to disrupt the phonological store but not the timing signal—should have its usual disruptive effect on serial recall but will not influence the Hebb effect nor the impact of inconsistent temporal grouping on the Hebb effect. And Hitch et al.'s (2009) data confirmed those predictions. However, the present Experiment 1 has already raised concerns about the suitability of the methodology used by Hitch et al. (2009) insofar as we found, using a more standard Hebb methodology, that the Hebb effect is indeed impaired by articulatory suppression (as well as affected by phonological similarity).

In the present experiment, therefore, we sought not only to replicate the effect of articulatory suppression on Hebb sequence learning but also to demonstrate that the effect of temporal grouping-inconsistency on such learning does indeed reflect the role of articulatory planning in verbal sequence learning, not the action of a non-articulatory ordering mechanism. The experiment involved two complementary analyses. First, following Maybery et al. (2002), we assessed the extent to which different presentation-groupings promote at least qualitatively similar groupings within participants' temporal organization of their responses as they output the sequence. To assess the extent to which any such output-grouping reflects the overt execution of a grouped articulatory-plan, we also examined for the first time whether or not the match been output- and presentation-timing is diminished under articulatory suppression. We predicted that when, according to the perceptual-motor account, serial recall is more purely based on articulatory planning—that is, with visual presentation—articulatory suppression will attenuate markedly the degree to which the output-RTs resemble the presentation-timing. With auditory presentation, in contrast, where the temporal organization of the presented sequence is likely to be replicated within output-RTs due to passive perceptual grouping processes that proceed regardless of any deliberate articulatory grouping (e.g., Jones et al., 2004), articulatory suppression should have less effect. The second analysis will then involve examining the extent to which the evidence for temporal grouping within the articulatory plan for serial recall (derived from the first analysis) maps onto the extent to which temporal grouping-inconsistency across repetitions of a sequence attenuates Hebb sequence learning. More specifically, we predicted that inconsistent grouping across repetitions of the Hebb sequence should impair Hebb sequence learning because such variability in presentation will invoke variability in the temporal structure of the articulatory plan generated in response to each iteration of the Hebb sequence. This effect of inconsistent grouping was expected to be particularly apparent when grouping is based predominantly on articulatory processes (i.e., with visual presentation) and that in turn will have been demonstrated through the greater effect of articulatory suppression on output-grouping during serial recall for visual compared to auditory sequences. We also predicted that articulatory suppression should again attenuate the Hebb effect, at least for visual sequences, and eliminate any impact of inconsistent grouping on that effect.

In sum, then, we examined the timing of serial recall-output as well as Hebb sequence learning for visual- and auditory-verbal sequences with or without articulatory suppression and, of most interest in the present experiment, we also manipulated the temporal grouping of the items; in particular, the temporal grouping of items was either consistent or inconsistent across repetitions of the Hebb sequence.

Method

Participants. One hundred and four students (18 males, 86 females) from Royal Holloway, University of London, aged 18-49 years (mean 20.22 years, SD = 4.05) took part in return either for course credits or a small honorarium.

Apparatus and Materials. The apparatus and materials were identical to those of Experiment 1 except that all sequences comprised permutations of the seven letters *F, H, K, L, Q, R,* and *Y* (i.e., the dissimilar set from Experiment 1). The duration of each item was always 400 ms but the items could be presented in a number of different temporal groupings: 2-2-3, 2-5, 3-2-2, 3-4, 4-3, or 5-2, where the numbers represent the number of items in each group and a hyphen a between-groups interval. The within-group inter-stimulus interval was 200 ms while the between-group interval was 1000 ms, resulting in an overall sequence length that varied between 4800 ms and 5600 ms from the onset of the first item to the end of the seventh item.

Design. The experiment involved four within-participant factors and one between-participants factor. The first within-participant factors was Grouping-consistency (referred to simply as ‘Grouping’ for the purposes of the analysis of output RTs): In the consistent-grouping condition, all sequences across a block of trials was presented with the same grouping (one of the six possible groupings) while in the inconsistent condition, all six groupings occurred 3 times across the block of trials, once each for each instance of the Hebb sequence and twice each for Filler sequences. The other three within-participant factors were Articulatory suppression (no-suppression, with-suppression), List-type (Hebb, Filler), and Cycle (1-6). The between-participants factor was Modality of presentation, with 52 participants receiving the sequences visually and 52 participants receiving the sequences auditorily. Each Modality group received four blocks of trials, each consisting of 18 sequences of seven letters and in which every third sequence (starting with trial 3) was the same (Hebb) sequence, amounting to 6 instances of the Hebb sequence within a given block. These four blocks corresponded to the 2 × 2 combination of Grouping-consistency (consistent, inconsistent) and Articulatory suppression (with-suppression, no-suppression) and the four blocks were presented in one of four possible orders: A1-B2-A2-B1, A2-B1-A1-B2, B1-A2-B2-A1 or B2-A1-B1-A2, where A represents the no-suppression condition, B represents the with-suppression condition, 1 represents the consistent-grouping condition and 2 the inconsistent-grouping condition. In the inconsistent-grouping condition, where the Hebb sequence, across the block, was presented in all six possible groupings, it was ensured that particular organizations containing the same groups, such as the first group in 2-2-3 and 2-5, were not used for the Hebb sequence in successive cycles. For each block, the participant received one of two possible counterbalanced sets of sequences (unique to each block) with different item-orders for both the Hebb sequences and the filler sequences. In the consistent-grouping block, of the 52 participants in each Modality group, 9 participants received the 2-5 grouping in the no-suppression block and the 2-4 grouping in the with-suppression block, while 9 participants received the converse. Another 9 participants received the 4-3 grouping in the no-suppression block and the 5-2 grouping in the with-suppression block, while 9 participants received the converse. A further 8 participants received the 3-2-2 grouping in the no-suppression block and the 2-2-3 grouping in the with-suppression block, while 8 participants received the converse.

Procedure. The procedure was the same as for Experiment 1 except that each participant took part in only one session lasting approximately 1 hr.

Results

Output RTs during serial recall. Figure 3 shows the extent to which output RTs during mouse-click driven serial recall of the filler sequences presented during the inconsistent-grouping block aligned with the timings of the items as-presented for each of the six groupings as a function of Articulatory suppression and Modality. In the absence of suppression, with only two exceptions (cf. 5-2 grouping and part of the 3-2-2 grouping), there was a high degree of alignment between presentation and output timings, with RTs, once output was initiated, tending to be longest at group boundaries,

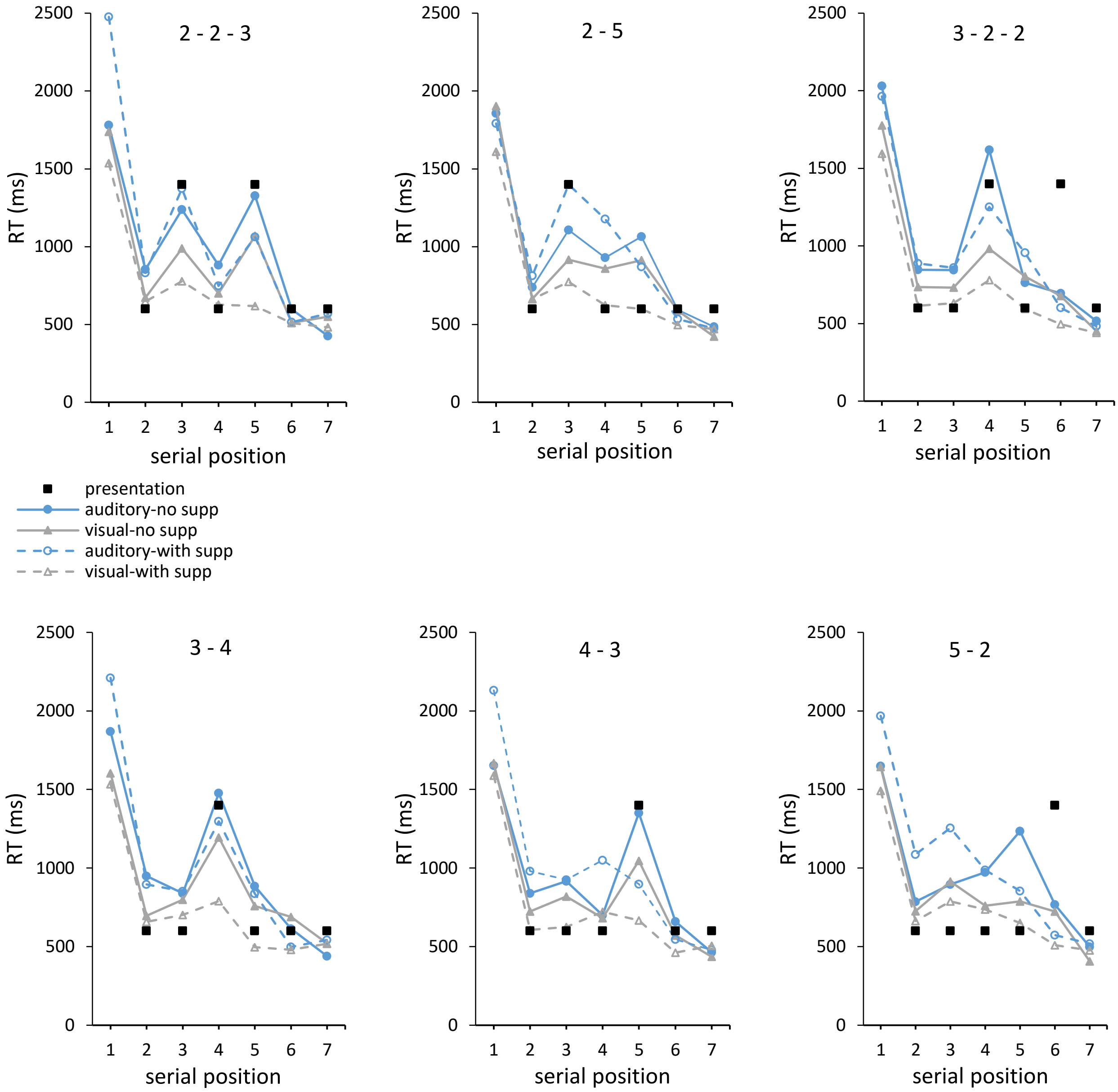

Figure 3. Presentation timing and output reaction times during serial recall within each of the six grouping conditions (within the inconsistent-grouping block) according to modality, suppression and position in Experiment 2.

indicating a temporal organization of responses that mimicked how the items were presented. Of particular interest is that with visual sequences, as predicted, this output-grouping was greatly attenuated under articulatory suppression, consistent with our supposition that with visual presentation (where there can be no passive auditory organization/grouping of the items) the output RTs reflect how the items are deliberately assembled into an articulatory plan. Accordingly, with auditory presentation, the alignment of input and output grouping is still very much evident even with articulatory suppression. Thus, the output-grouping effect with auditory, unlike visual, presentation, is not reliant to any large extent on articulatory planning but rather reflects, we would argue, the direct use of the way in which the auditory system has organized the input (cf. Jones, Beaman, & Macken, 1996).

These observations were supported first by a mixed ANOVA applied to the output-RTs which indicated a significant interaction of Modality, Articulatory suppression, Grouping and Serial position, $F(15.3, 1557.9) = 1.71$, $MSE = 605565.9$, $p = .042$, $\eta_p^2 = .016$ (Greenhouse-Geisser corrected). Other significant effects subsumed within this interaction are reported in Table A3 in the Appendix. We also examined the unevenness of the curves shown in Figure 3 (excluding serial position 1 in each case) as a measure of the degree of grouping in each of the four [Modality(2) x Suppression(2)] conditions within each grouping condition (wherein unevenness would be indicative of grouping). Following an approach taken by Salthouse (2010), we took, for each participant, the standard deviation (SD) of the output-RTs across serial positions 2-7 in each grouping condition, where a relatively large SD value would indicate a relatively uneven curve. A 2(Modality) x 2(Suppression) x 6(Grouping condition) ANOVA on the SD values showed a main effect of Modality, $F(1, 102) = 34.05$, $MSE = 404167.3$, $p < .001$, $\eta_p^2 = .25$, a main effect of Suppression, $F(1, 102) = 15.63$, $MSE = 167900.4$, $p < .001$, $\eta_p^2 = .13$, and, most critically, a reliable interaction between Modality and Suppression, $F(1, 102) = 8.11$, $MSE = 167900.4$, $p = .005$. $\eta_p^2 = .07$. Grouping did not interact with any other variable in this analysis (*p*s all < .13). A simple effects analysis of the reliable Modality by Suppression interaction, which is clearly evident in Figure 4, showed that with auditory lists, there was no difference in the SD as a function of articulatory suppression (p = .44). In contrast, with visual lists, the SD was significantly attenuated under articulatory suppression (p < .001).

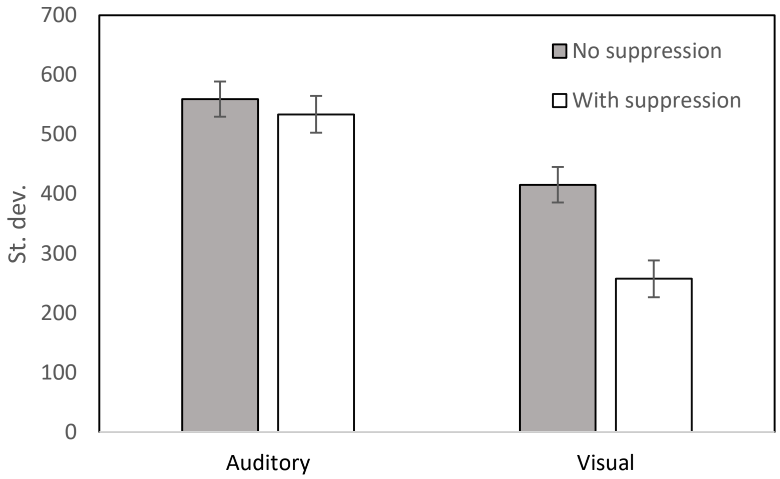

Figure 4. Standard deviation (St. dev.) of the output-RTs across serial positions 2-7 (cf. Figure 3) as a function of Modality and Suppression, collapsed over grouping condition in Experiment 2. Error bars show the standard error of the mean.

Hebb sequence learning. Turning now to Hebb sequence learning, Figure 5 shows recall performance accuracy across cycles with visual lists (Panels A and B) and auditory lists (Panels C and D) as a function of Grouping-consistency and Articulatory suppression. It is evident that with visually-presented lists (Panels A and B)—for which the output-RTs analysis suggested a high degree of articulatory-plan based grouping—learning was considerably weaker with inconsistent grouping of the repeated sequence. In addition, as in Experiment 1, learning with visual sequences was markedly attenuated under articulatory suppression regardless of grouping-consistency. Indeed, the learning of visual sequences appears to have been abolished by suppression in this experiment. Inevitably, therefore, the impact of inconsistent grouping on the Hebb effect did not survive articulatory suppression.

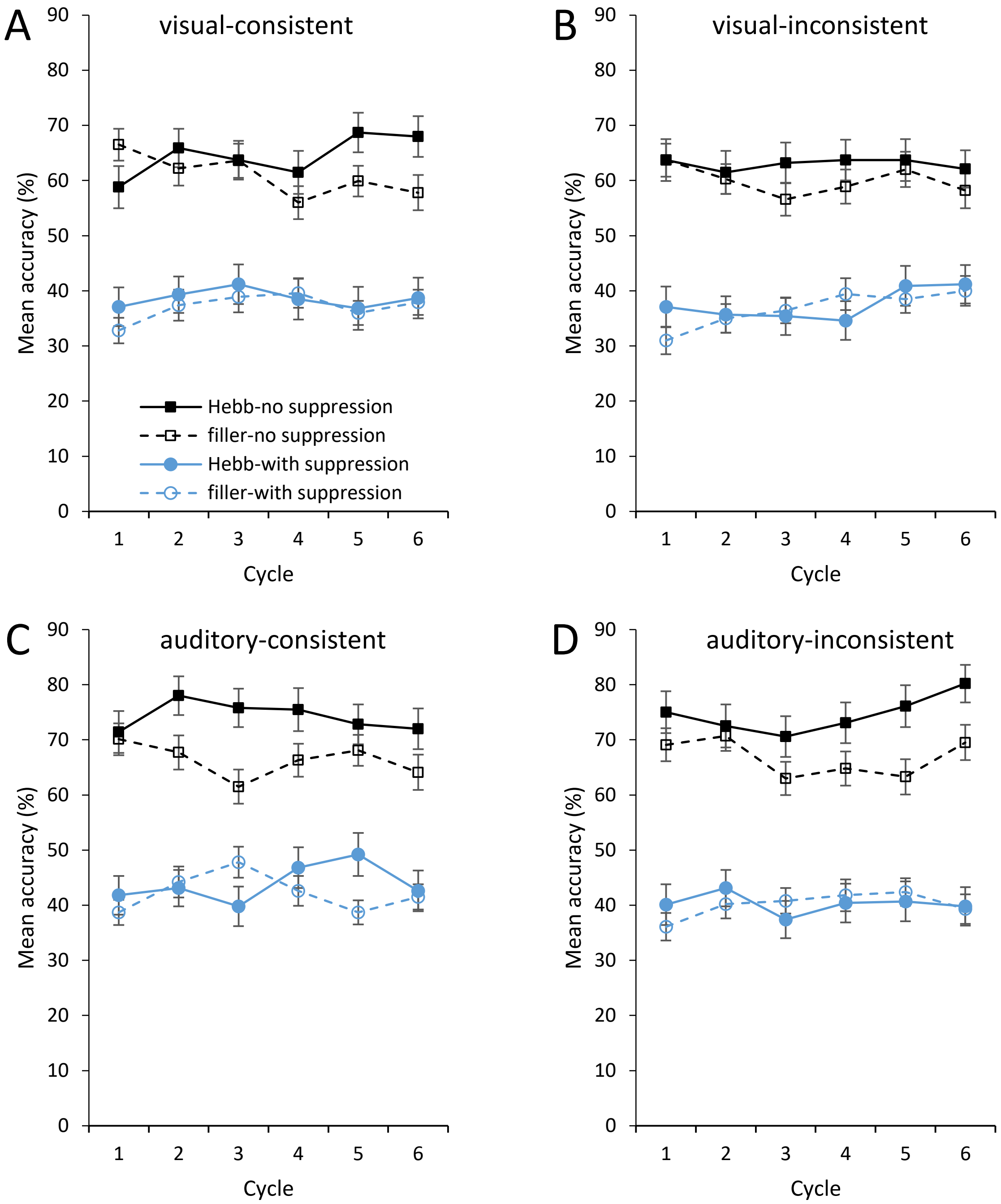

Figure 5. Performance accuracy across Cycles by List-type and Suppression conditions according to Modality and Grouping.

In contrast, with auditory sequences (Panels C and D)—for which the output-RTs suggested grouping but grouping driven by passive perceptual organization rather than articulatory planning—there was little evidence of an effect of inconsistent grouping on the Hebb effect. Thus, only when the grouping is driven solely by articulatory planning (i.e., with visual sequences) does grouping-inconsistency have a strong disruptive effect on sequence learning. Moreover, while suppression again markedly attenuated learning with auditory sequences, this attenuation was not as emphatic across cycles as was the case with visual sequences (see Panel C).

A 2 (List-type) × 2 (Modality) × 2 (Articulatory suppression) × 2 (Grouping-consistency) × 6 (Cycle) mixed-design ANOVA showed reliable main effects of List-type, $F(1, 102) = 20.93$, $MSE = .07$, $p < .001$, $\eta_p^2 = .17$, Articulatory suppression, $F(1, 102) = 497.71$, $MSE = .18$, $p < .001$, $\eta_p^2 = .83$, and Modality, $F(1, 102) = 10.93$, $MSE = .45$, $p = .001$, $\eta_p^{\,2} = .097$. There was also a significant interaction between List-type and Articulatory suppression, $F(1, 102) = 8.71$, $MSE = .07$, $p = .004$, $\eta_p^{\,2} = .079$, replicating the attenuation of Hebb sequence learning by articulatory suppression observed in Experiment 1. Corroborating our impressions of the pattern evident in Figure 5, the five-way interaction was also significant, $F(1.9, 200.3) = 4.38$, $MSE = .02$, $p = .014$, $\eta_p^{\,2} = .041$ (for the full set of results from this ANOVA as well as a simple effects analysis of the 5-way interaction, see, respectively, Tables A4 and A5 in the Appendix). Of particular relevance, the enhanced recall of the Hebb compared to filler sequences was reliable by cycles 5 and 6 in the visual-consistent condition ($p = .023$ and $p = .017$ respectively) while there was no reliable Hebb effect at any cycle in the visual-inconsistent condition (all *p*s > .05). For auditory sequences, without suppression, there was a Hebb effect at all cycles except cycles 1 and 5 in the consistent-grouping condition (though only marginal at cycle 6, $p = .066$) but, in contrast to the case with visual sequences, there was clear learning also in the inconsistent-grouping condition, with either a reliable effect or marginally reliable effect observed at all cycles except the first two (see Table A5 in the Appendix). Under suppression, there remained some evidence of learning with auditory sequences, though only at one cycle within the consistent-grouping condition (Cycle 5, $p = .016$).

Discussion

The results of Experiment 2 provide convergent support for a key role for articulatory planning in verbal sequence learning. First, we replicated the finding from Experiment 1 that when articulatory planning is restricted by articulatory suppression, learning is diminished markedly; indeed, for visual sequences, it was abolished in the present experiment. There was again some evidence of the learning of auditory sequences being more resistant to articulatory suppression than visual sequences: While only apparent at one cycle in the consistent-grouping condition, it remains the case that only with auditory sequences was there any evidence of learning surviving the otherwise emphatic impact of articulatory suppression. Turning to the novel aspects of the present experiment, we showed first that RT-indexed output-grouping during serial recall is diminished dramatically under articulatory suppression but only with visual presentation, where there can be no passive, auditory-perceptual based, grouping. When such passive auditory grouping can occur (i.e., with auditory sequences) the grouping remained strong under suppression. Thus, the output grouping in the auditory case appears to reflect a direct motoric translation of the way in which passive perceptual process have organized the input. Second, this pattern in the RT data mapped systematically onto the pattern of verbal sequence learning: Only when the grouping was dependent on articulatory planning (i.e., with visual sequences) did an inconsistency in the presented-grouping across Hebb repetitions attenuate (indeed eliminate) learning. We contend that the inconsistency in the input-grouping across the repeated sequence produced a corresponding inconsistency in the articulatory plan generated for its serial recall, thereby reducing the articulatory fluency-gain that is otherwise made from repeatedly planning the same sequence.

When the sequence was subject to auditory perceptual organization as well as articulatory planning (i.e., auditory, no-suppression condition), learning was evident regardless of grouping-inconsistency across repetitions. One possibility is that the co-occurrence of articulatory planning and auditory-perceptual processes provides sufficiently strong cues to the order of successive items to resist the otherwise disruptive impact on learning of a change in the way the items are organized into sub-groups across repetitions. This may also account for the particularly strong and rapid learning found for the auditory-dissimilar sequences in Experiment 1 (but not similar sequences, where acoustic-order cues would be weak). Further research will be required to examine this tentative account of this particular finding however.

The findings of this experiment are again problematic for Burgess and colleagues' account. Not only was the attenuating effect of articulatory suppression on Hebb sequence learning replicated, temporal grouping effects interacted with presentation-modality: The effect of inconsistent grouping only affected learning with visual, and not auditory, sequences. This is directly at odds with the finding of Hitch et al. (2009) who found a disruptive effect of inconsistent grouping using auditory sequences (they did not include a visual condition), raising again the concern that non-standard aspects of their particular method (e.g., 12-item lists, item-set overlap between filler and Hebb sequences) may have led to results that are not replicable under more standard conditions.[5]

A potential counterargument to the interpretation of the grouping effects in Experiment 2 as having an articulatory-planning locus, however, could be based on a study by Farrell and Lelievre (2012), the results of which are sometimes interpreted as demonstrating that grouping at output reflects the structure of memory storage during encoding, not articulatory planning. Farrell and Lelievre (2012) asked participants to start

[5] Bower and Winzenz (1969) also reported that the Hebb effect was attenuated with inconsistent grouping with auditory sequences (again, they did not include visual sequences). However, this result is also difficult to interpret: In the relevant experiments (Experiments 3-4, 6-8), few details about the structure and timing of the groupings used are provided and the power of the experiments was relatively low (*n* = 10-18 compared with *n* = 104 in the present experiment). Moreover, that study, like Hitch et al. (2009), used unusually long lists of 12 items.

serial recall of a list at various serial positions and then wrap back around to the beginning of the list (e.g., to recall items in positions 4-7 followed by those in positions 1-3) in an attempt to disentangle the role of input and output processes in output-grouping effects. They found peaks in both recall accuracy and RTs at group boundaries that were similar regardless of recall start-point, suggesting that temporal grouping at output reflects the structure of input-encoding into a short-term store, rather than processes related to the production of the output. However, as Farrell and Lelievre (2012) acknowledge, the results of their Experiments 1 and 2 only bring into question the idea that output-grouping effects reflect the action of a late-stage motor-output buffer and that they are still compatible with such effects reflecting the temporal structure of an articulatory plan generated during list presentation. Indeed, their final experiment (Experiment 3) was specifically designed to try to also rule out an articulatory planning account. The results of that experiment are ambiguous: While impeding articulatory planning through articulatory suppression was found to have little effect on output-grouping as evident from RTs, it did attenuate grouping as evident in recall accuracy (see also Hitch et al., 1996). Doubts can be raised also about the effectiveness of their articulatory suppression manipulation insofar as they used steady-state suppression ("blah, blah, blah...") which, as noted, is significantly less effective at impeding articulatory planning than changing-state suppression (e.g., "eight, nine, ten…") such as used in the current study (cf. Macken & Jones, 1995). The rate of suppression was also rather slow in Farrell and Lelievre (2012): approximately two items/s compared to the more typical rate of approximately three items/s as used in the present experiments. We suggest that their findings are not, therefore, as troubling for an articulatory planning account of output-grouping effects as often thought. Furthermore, the current interaction between modality and articulatory suppression in relation to the output-RTs, where grouping was diminished under suppression only for visual sequences, is particularly adjudicative: This interaction is precisely as predicted by an account in which there are two sources of grouping, one articulatory-planning based and another passive perceptual-organisation based source with auditory sequences. Such an interaction is not, however, predicted by an account where output-grouping has a single, input-storage, basis.

General Discussion

The present findings provide strong support for an articulatory-planning basis to Hebb verbal sequence learning and disconfirm basic assumptions of an alternative, phonological-store based, account (Burgess & Hitch, 2006). Contrary to previous studies (Hitch et al., 2009; Page et al., 2006), both experiments here showed that restricting articulatory planning through articulatory suppression attenuates not only the short-term serial recall of a verbal sequence but also Hebb sequence learning, particularly for a visually-presented sequence in which there can be no contribution to learning of passive auditory perceptual organization processes that bypass articulatory processes (Jones et al., 2004). This result is inconsistent with the notion of a dissociation in which articulatory suppression affects short-term item storage but does not impair the mechanism by which a repeating sequence is learned. (Burgess & Hitch, 2006; Hitch et al., 2009). Further support for an articulatory basis to verbal sequence learning came from the impact of phonological similarity in Experiment 1: The larger Hebb effect for phonologically similar sequences with visual presentation can be explained by supposing that the articulatory planning of such a sequence stands more to gain from repeated practice than the relatively more fluent plan associated with a phonologically dissimilar sequence (e.g., Heathcote et al., 2000). Again, the Burgess and colleagues model denies that phonological similarity should modulate Hebb sequence learning due to the model's two-stage architecture. A third converging line of support for the role of articulatory planning in Hebb sequence learning came from the relation observed in Experiment 2 between the effect of temporal grouping on output-RTs during serial recall and grouping-inconsistency on the Hebb effect: With visual sequences (and only visual sequences)—for which there was strong evidence for articulatory-based grouping during serial recall that mimicked the presentation-grouping—grouping-inconsistency across the repetitions of the Hebb list eliminated the Hebb effect.

Based on the current results, we suggest that verbal sequence learning reflects the increasing fluency of an articulatory plan generated to retain and reproduce a verbal sequence over the short term. Repeated articulatory planning of a sequence may in particular enhance the co-articulation of the items—the process whereby the articulatory transition between one phonetic segment (*A*) and the next (*B*) is facilitated by the planning, and therefore accommodation of, the articulatory gestures required to produce the onset of *B* when articulating the end of *A* (e.g., Sternberg, Wright, Knoll, & Monsell, 1980). Other evidence consistent with this supposition is that practice at co-articulating a set of verbal items improves the capacity to serially recall those items over and above any enhancement attributable to increased familiarity with the individual items (Woodward et al., 2008). In our view, then, 'verbal rehearsal' is cast as a particular instantiation of general and constructive motor-sequencing processes that generate a new object (cf. Macken et al., 2016; Willingham, 1998) rather than as a process designed to counter a negative item-level mechanism within a dedicated verbal memory store (i.e., item-decay). From this perspective, short-term recall constitutes the overt production of the new (motor) object, not the iterative retrieval of representations residing in a non-motoric (phonological) store, while verbal sequence learning reflects the decreasing need to generate a new motor-object in response to a sequence that has already been (repeatedly) transformed into motoric form. In particular, studies of motor-skill learning (focusing typically on nonverbal actions) have emphasized the importance to learning of chunking whereby the movement-sequence elements are integrated into fewer but larger units (Sakai, Kitaguchi, & Hikosaka, 2003). The results of Experiment 2 show quite clearly the importance of this process in the verbal domain where, at least with visually-presented sequences, no learning takes place if the organization of the chunks changes across sequence repetitions.

The idea that Hebb sequence learning has a largely articulatory basis may at first glance seem at odds with studies indicating that the production of the repeating list during serial recall is not necessary for such learning (even with visual lists; Kalm & Norris, 2016; Oberauer & Meyer, 2009; but see Cohen & Johanson, 1967; Cunningham, Healy, & Williams, 1984). However, whether or not such *overt production* of the sequence is necessary for the Hebb effect does not speak directly to the role of the *covert planning* of the sequence. This is because participants in such studies are typically only informed after the presentation of the sequence whether or not overt recall is required (Kalm & Norris, 2016; Oberauer & Meyer, 2009). Thus, an articulatory plan for the recall response is likely to be assembled during presentation regardless of the identity of the subsequent cue due to the potential need for that plan. The few studies in which there was no requirement or reason to assemble an articulatory plan for the repeating sequence at all provide, in fact, convergent support for our position: No Hebb effect is observed under such conditions (Cunningham, Healy, & Williams, 1984, Experiment 2; Glass, Krejci, & Goldman, 1989). For example, one of Glass et al.'s (1989) experiments involved presenting a continuous auditory-verbal sequence in which a repeating sequence was embedded. Participants who were required only to monitor the sequence for discrepancies against a written transcript or to shadow it (i.e., they were not required to recall, or therefore generate an articulatory plan for, the repeating sequence) did not show a Hebb effect when the repeated sequence had to be recalled later. Perhaps a greater challenge to our account comes from studies in which overt production was found to be necessary for the Hebb effect, suggesting that articulatory planning is not sufficient (Cohen & Johansson, 1967; Cunningham et al., 1984, Experiment 1). However, this conclusion has been brought into doubt by the contrary results of a number of subsequent, better-controlled, studies (e.g., Kalm & Norris, 2016; Oberauer & Meyer, 2009).

Another potential challenge to our conclusion that articulatory sequence-planning plays a key role in Hebb verbal sequence learning could be based on the fact that the conclusion relies heavily on the view that articulatory suppression impairs verbal serial recall (and hence sequence learning) by impeding such planning (e.g., Baddeley, 2007; Jones et al., 2004). An alternative view is that articulatory suppression disrupts verbal serial recall, at least in part, because the verbal representations produced by the suppression activity interfere with representations of the to-be-remembered items (e.g., Lewandowsky & Oberauer, 2015). From this standpoint, such item-interference may also account for the disruptive effect of articulatory suppression on sequence learning and the present results would not therefore necessarily speak to the role of articulatory planning in such learning. However, there are several reasons to question this alternative item-interference account. First, as noted in the foregoing discussion, if instead of impeding articulatory sequence-planning (e.g., through articulatory suppression), such planning is simply unlikely to be used as a strategy due to a change in the nature of the task to be carried out on the repeating sequence, the result is the same: an attenuation of Hebb sequence learning (Glass et al., 1988). On the grounds of parsimony, the fact that the Hebb effect is attenuated in the absence of articulatory sequence-planning even without any extraneous input that could cause item-interference weakens somewhat the position that articulatory suppression may have attenuated sequence learning through item-interference. Second, the effect of articulatory suppression on verbal serial recall accuracy, on output-grouping, and on Hebb sequence learning in the present study interacted with presentation-modality. It is unclear why item-interference would affect visually-presented items more than auditorily-presented items. While some authors have suggested that auditory items are more resistant to task-irrelevant input due to their greater distinctiveness relative to visual items (Neath, 2000), this has been challenged by the finding that task-irrelevant sound is no less disruptive of the serial recall of auditory items than it is of the recall of visual items (Nicholls & Jones, 2002b). Third, a more general difficulty for the notion that articulatory suppression disrupts verbal serial recall through item-interference is that the effect exhibits little of the classic hallmark of interference in memory, namely, that such interference is a function of the structural similarity between the irrelevant input and the memoranda (e.g., Brown, Neath, & Chater, 2007; Keppel & Underwood, 1962): When Murray (1967) manipulated the similarity between what was to be articulated as part of the articulatory suppression and the identities of the to-be-remembered items—which were letter-names as in the present study—he observed only a very small effect of similarity (3.2%) and concluded that "the nature of the suppression sound was only a minor consideration in determining the size of the suppression effect" (p. 269; see also Macken & Jones, 1995). Indeed, the articulatory suppression need not be verbal at all; for example, irrelevant whistling is as disruptive as irrelevant verbal activity (Saito, 1998). Finally, if articulatory suppression interferes with representations of to-be-remembered items, then it would seem that any task involving the short-term retrieval of those items should be affected. However, only if the order of the items needs to be recalled is there a marked effect of articulatory suppression (Klapp, Marshburn, & Lester, 1983, Macken & Jones, 1995), in line with our view that the function of articulatory planning in a serial recall task is to temporally bind the successive items, not to refresh their individual contents (e.g., Hughes et al., 2009, 2016). For example, if instead of serial recall the task is to identify which item was missing from a list (e.g., a digit missing from a random permutation of 1-8)—a task that necessitates memory for each individual item but not their order—articulatory suppression has far less effect than if the items need to be serially recalled (Klapp et al., 1983; Macken & Jones, 1995). Similarly, articulatory suppression only disrupts free recall to the extent that participants use serial rehearsal to recall the items (Bhatara, Ward, Smith, & Hayes, 2009).

In addition to demonstrating a key role for articulatory planning, the present results also suggest an additional contribution of passive perceptual processes to verbal sequence learning when sequences are presented auditorily. For example, learning of such sequences was in general attenuated to a lesser extent by suppression compared to visually-presented sequences. There was also some indication of the added contribution of auditory perceptual organization when articulatory planning was unrestricted: First, phonologically dissimilar sequences—for which there is independent evidence for strong passive auditory order-encoding (e.g., Jones & Macken, 1995)—were particularly well learned with auditory compared to visual presentation (Experiment 1). Second, when perceptual organization and motor planning co-occurred (as opposed to either operating in isolation), learning was resistant to the otherwise deleterious effect of an inconsistent temporal grouping of the Hebb sequence across repetitions (Experiment 2).

In conclusion, the current experiments have demonstrated a key role for articulatory planning in verbal sequence learning, contrary to a prominent phonological-store based model of Hebb sequence learning (Burgess & Hitch, 2006). As such, the present study is the first to have extended the explanatory compass of the perceptual-motor account of verbal serial short-term memory (e.g., Hughes et al., 2016; Jones et al., 2004) to the issue of how short-term processing translates into long-term learning. Some further questions that arise from the present research, then, are the extent to which this theoretical approach might be applied successfully to other verbal sequence learning settings (e.g., paired-associate learning; Papagno & Vallar, 1995) and to the learning of non-verbal (or non-verbalizable) material. For example, it has been shown that just as verbal serial short-term memory tasks tend to engage vocal-articulatory planning processes, short-term recall of a sequence of hand movements (such as in sign-language) relies on the motor planning involved in producing hand gestures: Performance in this domain shows a ‘gesture similarity effect’ (cf. phonological similarity effect) a gesture-length effect (cf. word-length effect; Baddeley, Thomson, & Buchanan, 1975) and a motor-manual suppression effect (cf. articulatory suppression effect) (Wilson & Fox, 2007). Based on the perceptual-motor account, we would again expect the long-term learning of such sequences to be driven by the (nonvocal) motor processes deployed opportunistically to meet the demands of the short-term recall task.

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Author note

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Appendix

Table A1

Full set of results from the Modality × Phonological similarity × Articulatory suppression × Serial Position ANOVA on serial recall accuracy

	F	*MSE*	*p*	η_p^2
Modality	1.2	.07	.278	.02
Similarity	42.9	.09	< .001	.47
Suppression	176.12	.12	< .001	.78
Position	231.18	.08	< .001	.83
Modality × Similarity	5.58	.04	.022	.10
Modality × Suppression	9.07	.05	.004	.16
Similarity × Suppression	24.69	.06	< .001	.34
Modality × Position	33.54	.012	< .001	.41
Similarity × Position	14.97	.01	< .001	.23
Suppression × Position	1.88	.02	.084	.04
Modality × Similarity × Suppression	2.83	.04	.099	.06
Modality × Similarity × Position	16.08	.01	< .001	.25
Modality × Suppression × Position	1.31	.01	.253	.03
Similarity × Suppression × Position	4.39	.01	< .001	.08
Modality × Similarity × Suppression × Position	3.13	.01	.005	.06

Table A2

Full set of results from the List-type × Modality × Phonological similarity × Articulatory suppression × Cycle ANOVA conducted to assess Hebb sequence learning in Experiment 1

	F	*MSE*	*p* value	η_p^2
List-type	59.25	.19	< .001	.55
List-type × Modality	.28	.10	.602	.01
List-type × Similarity	< .001	.09	.993	.00
List-type × Suppression	7.8	.15	.007	.14
List-type × Cycle	7.64	.04	< .001	.14
List-type × Similarity × Cycle	1.73	.04	.064	.03
List-type × Suppression × Cycle	3.16	.04	< .001	.06
List-type × Modality × Similarity	5.06	.15	.029	.09
List-type × Modality × Suppression	.40	.15	.528	.01
List-type × Similarity × Suppression	.07	.12	.795	.00
List-type × Modality × Cycle	.29	.04	.987	.01
List-type × Modality × Similarity × Cycle	1.39	.04	.174	.03
List-type × Modality × Suppression × Cycle	1.37	.04	.184	.03
List-type × Suppression × Similarity × Cycle	.87	.04	.570	.02
List-type × Modality × Similarity × Suppression	4.6	.06	.037	.09
List-type × Modality × Similarity x Suppression × Cycle	.62	.04	.817	.01
Modality	.35	.29	.558	.01

Similarity	44.32	.27	< .001	.48
Suppression	220.24	.41	< .001	.82
Cycle	9.48	.04	< .001	.16
Modality × Similarity	12.47	.14	.001	.20
Modality × Suppression	8.5	.2	.005	.15
Similarity × Suppression	17.08	.24	< .001	.26
Modality × Cycle	2.77	.04	.002	.05
Similarity × Cycle	1.78	.04	.055	.04
Suppression × Cycle	.81	.04	.631	.02
Modality × Similarity × Suppression	.58	.12	.449	.01
Modality × Similarity × Cycle	1.36	.04	.188	.03
Modality × Suppression × Cycle	.87	.04	.569	.02
Similarity × Suppression × Cycle	2.62	.04	.003	.05
Modality × Similarity × Suppression × Cycle	1.08	.04	.372	.02

Table A3

Full set of results from the Modality × Articulatory suppression × Grouping × Serial position ANOVA conducted to assess the output RTs in Experiment 2

	F	MSE	p	η_p^2
Modality	27.54	2189694.6	< .001	.21
Suppression	7.97	1097956.9	.006	.07
Grouping	1.02	248171.6	.407	.01
Position	116.36	387491.4	< .001	.53
Suppression × Modality	5.97	1097956.9	.016	.01
Grouping × Modality	.416	248171.6	.838	.01
Position × Modality	11.74	387491.4	< .001	.10
Suppression × Grouping	1.36	233087.3	.237	.01
Suppression × Position	8.68	379563.2	< .001	.08
Grouping × Position	11.81	245722.7	< .001	.10
Suppression × Grouping × Modality	.345	233087.3	.885	.00
Suppression × Position × Modality	1.88	379563.2	.096	.02
Grouping × Position × Modality	2.1	245722.7	.001	.02
Suppression × Grouping × Position	2.65	255978.9	< .001	.03

Table A4

Full set of results from the List-type × Modality × Articulatory suppression × Grouping-consistency × Cycle ANOVA conducted to assess Hebb sequence learning in Experiment 2

	F	MSE	*p*	η_p^2
List-type	20.93	.03	< .001	.17
Grouping-consistency	1.97	.08	.164	.02
Suppression	497.71	.09	< .001	.83
Cycle	.921	.04	.467	.01
List-type × Modality	2.32	.07	.131	.02
List-type × Cycle	.83	.04	.529	.01
List-type × Suppression	8.71	.04	.004	.08
Suppression × Modality	3.11	.18	.081	.03
Grouping-consistency × Modality	.03	.08	.868	.00
Suppression × Cycle	2.31	.04	.043	.02
Cycle × Modality	.69	.04	.632	.01
Grouping-consistency × Cycle	1.51	.04	.185	.02
List-type × Grouping-consistency	.23	.06	.635	.01
Grouping-consistency × Suppression	.57	.1	.452	.01
Grouping-consistency × Cycle × Modality	.67	.04	.65	.01
Grouping-consistency × Suppression × Cycle	.39	.04	.854	.01
List-type × Suppression × Cycle	3.57	.04	.003	.03
List-type × Grouping-consistency × Cycle	.86	.04	.509	.01
Suppression × Cycle × Modality	.75	.04	.588	.01
List-type × Cycle × Modality	.25	.04	.938	.00
List-type × Suppression × Modality	2.53	.07	.115	.02
List-type × Grouping-consistency × Modality	.01	.06	.935	.00
List-type × Grouping-consistency × Cycle × Modality	.22	.04	.955	.00
Grouping-consistency × Suppression × Modality	1.08	.10	.301	.01
List-type × Grouping-consistency × Suppression	.07	.08	.789	.00
List-type × Grouping-consistency × Suppression × Modality	.02	.08	.871	.00
List-type × Suppression × Cycle × Modality	1.11	.04	.354	.01
Grouping-consistency × Suppression × Modality × Cycle	1.15	.04	.332	.01
List-type × Grouping-consistency × Suppression × Cycle	.76	.04	.576	.01
List-type × Grouping-consistency × Suppression × Modality × Cycle	4.38	.02	.014	.04

Table A5

Simple-effects analysis of the interaction of List-type, Modality, Articulatory suppression, Grouping-consistency and Cycle in Experiment 2

Modality	Grouping	Articulatory suppression	Cycle	Hebb – filler (SE)	*p*
Visual	Consistent	No suppression	1	-7.7 (4.2)	.071
			2	3.7 (4.6)	.421
			3	0.1 (4.0)	.973
			4	5.5 (3.8)	.151
			5	8.8 (3.8)	.023
			6	10.2 (4.2)	.017
		With suppression	1	4.3 (4.0)	.289
			2	1.9 (3.4)	.569
			3	2.3 (3.9)	.553
			4	-1.1 (4.0)	.785
			5	0.8 (4.3)	.847
			6	0.8 (4.0)	.836
	Inconsistent	No suppression	1	-0.1 (4.4)	.999
			2	1.2 (4.3)	.775
			3	6.6 (4.4)	.137
			4	4.8 (4.2)	.252
			5	1.8 (4.6)	.701
			6	3.8 (3.6)	.288
		With suppression	1	6.0 (3.8)	.117
			2	0.7 (3.3)	.837
			3	-1.0 (4.2)	.819
			4	-4.8 (4.2)	.259
			5	2.5 (4.0)	.536
			6	1.2 (3.6)	.735
Auditory	Consistent	No suppression	1	1.4 (4.2)	.746
			2	10.3 (4.6)	.027
			3	14.3 (4.0)	.001
			4	9.2 (3.8)	.017
			5	4.7 (3.8)	.223
			6	7.8 (4.2)	.066
		With suppression			
			1	3.0 (4.0)	.451
			2	-1.1 (3.4)	.744
			3	-8.0 (3.9)	.045
			4	4.3 (4.0)	.292
			5	10.4 (4.3)	.016
			6	1.1 (4.0)	.782
	Inconsistent	No suppression	1	5.9 (4.5)	.187

	2	1.8 (4.3)	.680
	3	7.6 (4.4)	.089
	4	8.2 (4.2)	.051
	5	12.8 (4.6)	.007
	6	10.7 (3.6)	.004
With suppression			
	1	4.0 (3.8)	.300
	2	2.9 (3.3)	.388
	3	-3.4 (4.2)	.414
	4	-1.4 (4.3)	.746
	5	-1.8 (4.0)	.655
	6	0.6 (3.6)	.875