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Effects of Practice Schedules on Speech Motor Learning

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Abstract

The aim of this study was to evaluate the effects of various practice schedules on learning a novel speech task. Forty healthy Cantonese speakers were asked to learn to produce a Cantonese phrase with two target utterance durations (2500 and 3500 milliseconds). They were randomly assigned to one of four learning conditions each completing a different practice schedule, namely Blocked only, Random only, Blocked-then-Random, and Random-then-Blocked. Two retention tests (one immediate and one delayed) and a transfer test were administered. The four groups of participants showed different patterns of learning but achieved comparable levels of performance at the end of the acquisition phase. However, participants in the Blocked only condition were less able to differentiate the two target durations than those in the Random only condition during retention. Furthermore, participants who received both blocked and random practice were less adversely affected by the secondary task during the transfer test than those who received either blocked or random practice alone. These findings suggest that mixed practice schedules are more effective than either blocked or random practice, especially in transferring the acquired speech motor skills to a cognitively demanding situation. The results have clinical implications regarding optimal practice schedules for treatment intervention.

Effects of Practice Schedules on Speech Motor Learning

Researchers in the field of motor learning have long been interested in how to optimize learning by manipulating practice schedules (Schmidt, 1988). Practice schedules such as blocked practice (i.e., different targets practiced in separate successive blocks) and random practice (i.e., different targets intermixed in each practice block) have received much attention in the past (Brady, 1998; 2008; Lee & Simon, 2004; Magill & Hall, 1990; Rendell, Masters, & Farrow, 2009; Shea & Morgan, 1979). The general findings are that, relative to random practice, blocked practice leads to better performance during acquisition but poorer performance in retention or transfer tests.

Various explanations have been proposed to account for the differential outcomes of blocked and random practice. For instance, the elaboration hypothesis proposed by Shea and colleagues (Shea & Morgan, 1979; Shea & Zimny, 1983) suggests that, relative to blocked practice, random practice fosters a more elaborate memory representation of the similarities and differences of the various motor responses (because different motor tasks are compared and contrasted within the same block), and hence results in better retention of the acquired motor skills. Alternatively, other researchers (Lee & Magill, 1983; Lee, Magill, & Weeks, 1985) have proposed that the need for random learners to repeatedly retrieve and reconstruct motor plans across trials leads to better retention of the motor solutions (referred to as the reconstruction hypothesis). Blocked learners presumably can buffer most of the movement specifications for a task in working memory for use on the next trial, whereas random learners must reconstruct the entire motor plan on each trial. Consequently, the learning of each aspect of the motor skill is strengthened.

Apart from these two accounts, there is a small amount of evidence to suggest that the retention benefits of random practice are subserved by mechanisms of implicit motor learning (Rendell, Masters, Farrow, & Morris, 2010). Specifically, random practice is cognitively more demanding than blocked practice because of the need for task-switching (Li & Wright, 2000), and the augmented cognitive load prevents random learners from consciously testing and accumulating explicit movement-related rules (Rendell et al., 2010). Consequently, random learners acquire the motor skills in a relatively more implicit manner and rely less on explicit conscious processes that can adversely affect performance (e.g., Masters, 1992). As it has been demonstrated that implicitly learnt motor skills are longer lasting and more resistant to stress than explicitly acquired motor skills (e.g., Koehn, Dickinson, & Goodman, 2008; Liao & Masters, 2001; Masters, 1992; Masters & Maxwell, 2008; Masters & Poolton, 2012; Maxwell, Masters, Kerr, & Weedon, 2001; Poolton, Masters, & Maxwell, 2005; 2006; 2007), a retention benefit is therefore evident among random learners relative to blocked learners.

In addition, it has been shown that the effect of practice schedule varies as a function of the learner's skill level, with novices benefitting more from blocked practice and more skilled performers from random practice (Hebert, Landin, & Solmon, 1996). As one's skill level normally increases with the amount of practice (Newell & Rosenbloom, 1981), some researchers have proposed that the optimal practice schedule should be one that includes initial blocked practice followed by random practice (Boyce, Coker, & Bunker, 2006; Porter & Magill, 2010; see also the challenge-point hypothesis proposed by Guadagnoli & Lee, 2004). Indeed, in two experiments using different motor learning tasks (i.e., golf putting and basketball passing), Porter and Magill (2010) observed that learners who received blocked practice at the beginning and random practice at the end of the acquisition phase outperformed those who received either blocked or random practice alone, suggesting that a mixed practice schedule (i.e., including both blocked and random practice) is better than a pure one (i.e., either blocked or random practice). However, Porter and Magill (2010) did not include a condition in which the acquisition phase began with random practice and was followed by blocked practice. As such, it remains unknown whether the learning benefits observed in their mixed practice schedule condition were due to the presentation order, variety or both.

The studies reviewed above all come from the literature on limb motor learning. Generalization from these studies to other areas of motor learning, such as speech motor learning, cannot be assumed (e.g., Tse, Masters, Whitehill, & Ma, 2012; see Maas et al., 2008, for a review). Several studies investigating the effects of blocked practice and random practice on speech motor control have been reported, and the findings are in general, but not completely, consistent with those from limb motor learning research (Adams & Page, 2000; Knock, Ballard, Robin, & Schmidt, 2000; Maas & Farinella, 2012; Wong, Ma, & Yiu, 2011). Adams and Page (2000), for instance, employed an utterance duration control task in which participants were asked to produce an English phrase “Buy Bobby a poppy” with two designated utterance durations, 2400 ms, which is approximately two times slower than normal speech rate, and 3600 ms, which is approximately three times slower. Participants were randomly assigned to either a blocked learning or a random learning group, and each received a total of 50 practice trials during the acquisition phase. Participants in the blocked learning group practiced producing the two target durations (i.e., 2400- and 3600-ms utterances) in blocks of 25 trials, whereas those in the random learning group practiced in a randomized sequence. Feedback on utterance duration was given after each practice trial. Interestingly, while no significant group difference was observed in performance during acquisition, participants from the random learning group outperformed those from the blocked learning group in a retention test two days after the acquisition phase. Adams and Page (2000) concluded that the retention benefits of random practice, relative to blocked practice, can be generalized to speech motor learning. Knock et al. (2000) compared the effects of blocked and random practice among impaired speakers (i.e., individuals with apraxia of speech and aphasia), and observed a similar pattern of results.

To better understand the relationship between practice schedules and speech motor learning, the findings discussed above should be interpreted with reference to the mechanism of speech motor control. According to the Four-level Framework proposed by Van der Merwe (1997), speech production encompasses four major phases. First is a pre-motor linguistic-symbolic phase in which abstract ideas are transformed into meaningful linguistic codes for the subsequent (speech) motor specifications. Second is speech motor planning, in which the *strategy* for speech action is defined. Specifically, each speech phoneme has a core motor plan including a set of speech motor goals (e.g., lip closure, velar rising, vocal fold closure etc.). Each speech motor goal contains information regarding the spatial (place and manner of articulation) and temporal specification of the movement. During speech motor planning, the speech motor goals are identified and arranged in order. In addition, adaptation of the core motor plan occurs at this stage during which the rate of speech is adapted to the speech context. Third is speech motor programming, in which the *tactics* for realizing the motor plans are defined. Specifically, the muscles necessary for achieving the speech motor goals are specified. Fourth is execution during which the specifications are relayed to the corresponding motor effectors and transformed into actual movements.

With reference to the Four-level Framework, participants in the Adams and Page (2000) study were required to recall and execute the same set of core motor plans in each practice trial (since the same target utterance was repeatedly produced during acquisition) but to attain two novel adaptations of the articulatory movement, each specifying a particular utterance duration (i.e., 2400 or 3600 ms). External feedback (e.g., knowledge of results of utterance duration) was used during acquisition to guide the adjustment of the speech rate to achieve the two target durations. Note that the specification of speech rate is hypothesized to have been made during speech motor planning via adaptation of the core motor plans. Accordingly, the retention benefits of random practice over blocked practice can possibly be accounted for by a better memory representation of the specifications involved in speech rate adaptation (elaboration hypothesis), more thorough practice of the various speech motor processes (reconstruction hypothesis), or by advantages associated with implicit characteristics that are arise from random practice of the speech task but not blocked practice. These three proposed accounts of the benefits of random practice in speech motor learning are not mutually exclusive; it is plausible that the advantage of random practice is sub-served by multiple factors.

Although, as we have pointed out, there is some evidence showing the benefits of random practice over blocked practice in speech motor learning, the effect of mixed practice schedules in speech motor learning has not been systematically investigated before. It is unclear whether the mixed schedule advantage observed by Porter and Magill (2010) can also be found in speech motor learning. The present study was conducted to address this issue by using an utterance duration control task similar to Adams and Page (2000). Specifically, four learning conditions with different practice schedules were included in this study, namely Blocked only, Random only, Blocked-then-Random, and Random-then-Blocked. Note that a mixed practice schedule was included in the last two conditions, and the only difference between the two was the presentation order of blocked and random practice. If the mixed schedule advantage observed by

Porter and Magill (2010) is applicable to speech motor learning, participants from the Blocked-then-Random condition should perform better than those from Blocked only or Random only conditions in both retention and transfer tests. A secondary task was employed in the transfer test in which participants needed to complete the primary utterance duration control task *and* a secondary key-pressing task simultaneously. The rationale for this was that the better the primary speech task was learnt (i.e., more automatic), the less performance would be adversely affected by a cognitively demanding secondary task (e.g., MacMahon & Masters, 2002; Maxwell, Masters, & Eves, 2003). A variant of the Flanker's response competition (key-pressing) task (Erikson & Erikson, 1974) was used as the secondary task because this type of task has been widely adopted to investigate the availability of attention resources (e.g., Green & Bavelier, 2003; Lavie, Hirst, de Fockert, & Viding, 2004). Also, the manual response required by the key-pressing task did not overlap with the motor processes entailed in speech production. Therefore, any effects of the secondary task on the primary speech task could be attributed to the augmented central attention demands (Kahneman, 1973) and used to reflect the automaticity of the primary speech motor response.

In addition, this study was also designed to verify the source of the mixed schedule advantage (if any). If the presentation order of blocked and random practice (i.e., blocked first followed by random practice) is crucial for a mixed schedule advantage to arise, then one would expect to see better learning outcomes in the Blocked-then-Random condition than in the Random-then-Blocked condition. On the contrary, if the mixed schedule advantage is due to its relatively high variety of practice (in terms of the types of practice schedules included), then comparable learning outcomes would be expected between the two mixed schedule conditions in this study.

Method

Participants

Forty Cantonese-speaking undergraduates (26 females; mean age: 20.8 years, SD = 1.6) with normal or corrected-to-normal vision, and without a prior history of speech or hearing impairment were recruited from the University of Hong Kong. Written informed consent was obtained from all participants prior to commencing the experiment. Each participant received oral debriefing and a sum of HK$80 (approx. US$10) for their participation. Ethical approval was obtained from the Human Research Ethics Committee for Non-Clinical Faculties of the University of Hong Kong.

Task and Apparatus

Primary task. The primary task, used for training and testing acquisition of speech motor skills, was to produce a Cantonese phrase with six syllables over a specified duration of 2500ms (roughly two times slower than normal speech rate) or 3500ms (roughly three times slower than normal speech rate). The Cantonese phrase *pa4 pa1 pʰui4 pɔ1 pei2 pʰau2* (i.e., 爸爸陪波比跑 in written Chinese; meaning “Father jogs together with Bobby”; the number beside each syllable denotes the lexical tone of the syllable) was chosen as the target phrase, mirroring the phrase used by Adams and Page (2000). In the Adams and Page study with English speaking participants, the target phrase was “Buy Bobby a Poppy”, which includes six syllables (most simple syllables with a consonant-vowel structure) and bilabial consonants (see also Adams, Page, & Jog, 2002). Similarly, the target phrase adopted in the present experiment also included six simple syllables and bilabial consonants.

The utterances produced by participants were recorded by a microphone (Shure 450 series II) connecting to a Dell Pentium IV computer via an external soundcard (M-Audio Mobile PreUSB). The microphone was positioned at a distance of 10cm from the participant's mouth. Utterance durations were measured and analyzed online by the experimenter using Praat version 5.1 (Boersma & Weenink, 2008). The utterance duration values (in ms) were taken to reflect performance. A separate monitor connected to the same computer (dual monitor setting) was used to display visual feedback to the participant during the acquisition phase. The visual feedback is described in further detail below.

Secondary task. A secondary key-pressing task, used for diverting participants' attention from the primary speech task (i.e., utterance duration control task), was employed in the transfer test (also in the Pre-test for baseline measurement). In each trial of the task, a centered-fixation cross was first presented on the screen for 500 ms followed by a blank screen (500 ms). The target stimulus, a string of seven arrows in which the one in the middle was always underlined (e.g., <<<≤<<<), was then presented. The underlined arrow and the six surrounding arrows were either pointing in the same direction (i.e., congruent; e.g., <<<≤<<< or >>>≥>>>), or in the opposite direction (i.e., incongruent; e.g., <<<≥<<< or >>>≤>>>). Participants were asked to respond to the underlined arrow by pressing the corresponding key (i.e., left-shift for ≤ and right-shift for ≥) as fast as possible, and to ignore the remaining arrows. Response time was measured from the onset of the target display to the time when a response was detected. An independent Dell Pentium IV computer was used to record participants' response times, and to schedule presentation of stimuli by running DMDX (Forster & Forster, 2003). A schematic layout of the secondary task procedure is shown in Figure 1.

[Insert Figure 1 about here]

Design and Procedure

The study included pre-tests, acquisition phase, retention tests, and transfer test.

Pre-tests. At the beginning of the experiment, participants were asked to sit comfortably in front of a computer screen at a distance of approximately 70 cm, and to complete a key pressing task (described above), which was identical to the secondary task employed in the later transfer test. Altogether there were 16 trials in which congruent (n = 8) and incongruent (n = 8) stimuli were presented in a random order. The inter-trial interval was 1500-ms.

Following completion of the key pressing task, participants were asked to produce three trials of the target Cantonese phrase *pa4 pa1 pʰui4 pɔ1 pei2 pʰau2* at their habitual rate of speech. Each spoken utterance was recorded and displayed on the screen of the experimenter's computer (which could not be seen by the participant) and the experimenter measured the duration of the utterance using Praat. After completing all three trials, the duration value (in ms) of each trial was shown to the participant with a bar chart display (which was presented on the screen in front of the participant). In this way, visual feedback was given to the participants.

Acquisition phase. Participants were then randomly assigned to one of four groups (n = 10 participants in each) with different practice schedules. Group 1 practiced producing the 2500 and 3500-ms utterances in blocks of 40 trials each (Blocked only). Group 2 practiced producing the same two target utterances but in a randomized sequence of 80 trials (Random only). Group 3 practiced by first producing the two target utterances in two blocks of 20 trials, followed by a randomized sequence of 40 trials (Blocked-then-Random). Group 4 practiced producing the two target utterances in a randomized sequence of 40 trials first, followed by two blocks of 20 trials each (Random-then-Blocked). The order of blocked trials in the blocked practice conditions was counterbalanced across participants. In random practice conditions, trials were random with the constraint that the same trial did not appear more than three times consecutively. After each trial, visual feedback about utterance duration was immediately shown to the participant in the same way as described above (see *Pre-test*), and the experimenter verbally signaled the target duration of the next trial.

Retention tests. Two identical retention tests were administered to each participant following the acquisition phase. One was given immediately after the end of the acquisition phase, and the other was given two days after. During the retention test, participants were asked to produce 16 trials of the target Cantonese phrase in a mini-blocked schedule (e.g., two trials of 2500-ms utterance followed by two trials of 3500-ms utterance, then followed by another two trials of 2500-ms utterance and so on), which was a novel schedule for all participants. However, unlike the acquisition phase, no feedback was given in the retention tests. The order of trial presentation was counter-balanced across participants.

In each trial of the retention test, a centered-fixation cross was first presented for 500 ms followed by a blank screen (500 ms). After that, an auditory signal indicating the target utterance duration was presented by the computer via two loud speakers. The auditory signal was a Cantonese word (i.e., /tʃ'œŋ4 jɐm1/, meaning "long duration", or /tyn2 jɐm1/, meaning "short duration") pre-recorded by a male Cantonese native speaker. The next trial began 1000 ms after the participant had completed the utterance.

Transfer test. A transfer test was administered shortly after the second retention test. Participants were required to perform two tasks simultaneously and were told that the two tasks were equally important. The primary task was the speech task adopted in the retention tests following the same mini-blocked presentation schedule, whereas the secondary task was the key pressing task introduced in the pre-test. Similar to the retention test, auditory signals were used to indicate the target utterance duration in each trial. To ensure that participants treated the two tasks as equally important, two stimulus onset asynchrony (SOA) conditions were included. In one SOA condition, the auditory signal (i.e., /tʃ’œŋ4 jɐm1/ or /tyn2 jɐm1/) for the primary speech task was presented 400 ms earlier than the visual target (i.e., a string of arrows) for the key pressing task, whereas in the other SOA condition, the visual stimulus was presented 400 ms earlier than the auditory one. In each trial of the transfer test, a centered-fixation cross was first presented for 500 ms followed by a blank screen for 500 ms. After that the first stimulus (visual or auditory) was shown and then after a 400-ms delay the second stimulus (auditory or visual) was presented. The next trial began 1000 ms after the verbal response was completed.

Results

Intra-rater and Inter-rater Reliability

Both intra-rater and inter-rater reliabilities of utterance duration were measured. To assess the intra-rater reliability, 10% of all utterance responses were randomly selected; the same experimenter who was responsible for data collection conducted the measurement a second time after the experiment. Similarly, a naïve Cantonese-speaking research assistant was recruited to measure the duration of the randomly selected utterance responses independently. Intra-class coefficient (ICC: Absolute agreement) was used to gauge the degree of reliability (Shrout & Fleiss, 1979). The results showed high intra-rater (ICC = 0.99) and inter-rater (ICC = 0.98) reliabilities of utterance durations. In addition, all utterances recorded in the present study were perceptually correct tokens of the target Cantonese phrase and were used for duration analyses.

Utterance Duration Control Task

Pre-test. The mean utterance duration across all participants in the pre-test was 1564 ms (SD = 198 ms), and there were no significant differences across groups (F = 0.39; p = 0.76).

Acquisition Phase. Each participant received a total of 80 practice trials in the learning phase, including 40 trials with target duration of 2500 ms (i.e., short duration trials) and 40 trials with target duration of 3500 ms (i.e., long duration trials). To better understand participants' performance change throughout the learning phase, each participant's responses across every ten trials of the same target duration were grouped together for analysis. The root-mean-square error (RMSE) in utterance duration (in ms) was used as the crucial dependent variable to reflect participants' performance in achieving the target durations. A small RMSE value indicates a close match between the participant's utterance duration and the intended target, whereas a large RMSE value indicates a discrepancy between the two. Accordingly, four RMSE values for short duration trials (one for each 10-trial block) and four RMSE values for long duration trials (one for each 10-trial block) were obtained from each participant. The resulting RMSE values were taken for analyses.

Apart from the RMSE values, the mean difference in utterance duration across the short and the long duration trials for each participant was also measured to reflect participants' performance in differentiating the two target outputs. Generally speaking, the smaller the duration difference between the two types of output, the worse the performance of the participant in differentiating the two target durations. The optimal mean duration difference between short and long duration trials was 1000-ms.

RMSE analysis. A three-way analysis of variance (ANOVA) was performed to evaluate the effects of learning condition and target duration on participants' performance in the utterance duration control task. The dependent variable was RMSE in utterance duration (in ms). The between-subjects factor was Learning Condition with four levels (Blocked only, Random only, Blocked-then-random, and Random-then-blocked). The within-subjects factors were Target

Duration with two levels (2500-ms vs. 3500-ms utterance) and Trial Block with four levels (1^{st} , 2^{nd}, 3^{rd}, and 4^{th} 10-trial block). The effects were tested using the multivariate criterion of Wilk's lambda (Λ). A main effect was evident for Target Duration, $\Lambda = 0.87$, $F\ (1, 36) = 5.4$, $p = 0.026$ (mean RMSE 187±152 ms for short duration trials, 222±142 ms for long duration trials), and for Trial Block, $\Lambda = 0.29$, $F\ (3, 34) = 27.5$, $p < 0.001$. Furthermore, a significant Learning Condition x Trial Block interaction was also observed, $\Lambda = 0.33$, $F\ (9, 83) = 5.3$, $p < 0.001$. No other significant results were found (Fs ≤ 1.9, ps ≥ 0.14). The RMSE of participants' utterance durations in various conditions are shown in Figure 2.

[Insert Figure 2 about here]

There are two possible strategies to deconstruct the Learning Condition x Trial Block interaction. One is to look at the effect of Trial Block on participants' performance in each of the four learning conditions separately; another is to investigate the effect of Learning Condition on participants' performance in each trial block. Since the effects of Learning Condition in various phases of acquisition are more relevant to the aim of the current study, we decided to adopt the latter approach. Accordingly, four separate one-way ANOVAs were conducted to investigate the effects of Learning Condition in each of the four trial blocks.

The effect of Learning Condition was significant in the 2^{nd} and the 3^{rd} trial blocks [$F\ (3, 36) = 8$, $p < 0.001$, and $F\ (3, 36) = 3.5$, $p = 0.025$, respectively] but not in the 1^{st} and the 4^{th} trial blocks (Fs ≤ 2, ps ≥ 0.12). Subsequent pairwise comparisons with Bonferroni correction were conducted to compare the mean RMSE values across learning conditions in the 2^{nd} and the 3^{rd} trial blocks. In the 2^{nd} trial block, the mean RMSE in the Blocked only condition was significantly lower than the Random only ($p = 0.032$) and the Random-then-Blocked conditions ($p = 0.006$). Similarly, the mean RMSE in the Blocked-then-Random condition was significantly lower than the Random only (p = 0.015) and the Random-then-Blocked conditions (p = 0.003). No other significant results were found (ps > 0.5). In the 3rd trial block, the difference between Blocked only and Random only conditions as well as between Blocked only and Blocked-then-Random conditions was marginal (p = 0.081 and p = 0.065, respectively). No other comparisons reached significance (ps > 0.47).

Mean duration difference analysis. The overall difference in utterance duration between short and long duration trials was 883 ms (SD = 114), and no significant differences were observed across learning conditions (F = 1.49, p = 0.23).

Post-tests. Participants' performance in the three post-tests was analyzed in the following manner. First, a 2 (Retention Period: Immediate vs. Delayed Retention) x 2 (Target Duration) x 4 (Learning Condition) ANOVA was performed on the data from the two retention tests, to evaluate the *effect of retention period* on participants' performance in the utterance duration control task. Second, the data from the delayed retention test and transfer test were submitted to a 2 (Testing Condition: Without a 2nd Task vs. With a 2nd Task) x 2 (Target Duration) x 4 (Learning Condition) ANOVA, to evaluate the *effect of secondary task* (i.e., key pressing task) on participants' performance in the primary speech task. Similar to the acquisition phase, the RMSE in duration and the mean duration difference between short and long duration trials were the two important dependent variables to assess participants' performance in post-tests.

Effect of retention period.

RMSE analysis. The main effect of Retention Period was significant, $\Lambda = 0.66$, F (1, 36) = 18.6, $p < 0.001$ (mean RMSE 265±126 ms for the immediate retention test, 410±227 ms for the delayed retention test). No other significant results were obtained (Fs ≤ 2.3, ps ≥ 0.1). The RMSE results in various conditions are shown in Figure 3.

[Insert Figure 3 about here]

Mean duration difference analysis. In addition, the mean duration difference between short and long duration trials for each participant was submitted to a 2 (Retention Period) x 4 (Learning Condition) ANOVA. A significant main effect of Learning Condition was found [F (3, 36) = 4.7, p = 0.007] but no other significant results were obtained (Fs $\leq$ 2.2, ps $\geq$ 0.15). Subsequent pairwise comparisons with Bonferroni correction showed that the mean duration difference in the Blocked only condition was significantly smaller than the Random only and the Blocked-then-Random condition, p = 0.012 and p = 0.027, respectively. No other significant comparisons were observed (ps $\geq$ 0.5). Mean duration differences in the learning and testing conditions are shown in Table 1.

[Insert Table 1 about here]

Effect of secondary task.

RMSE analysis. The main effect of Testing Condition was significant, Λ = 0.85, F (1, 36) = 6.5, p = 0.015, indicating that the RMSE value was higher when the secondary task was imposed (490±361 ms) than when it was not imposed (410±227 ms). In addition, a marginal Testing Condition x Target Duration interaction was found, Λ = 0.92, F (1, 36) = 3.2, p = 0.081. No other significant results were obtained (Fs $\leq$ 2.2, ps $\geq$ 0.1). RMSE of utterance durations in the various conditions are shown in Figure 4.

[Insert Figure 4 about here]

Although the Learning Condition x Testing Condition interaction was not significant, inspection of Figure 3 suggests that the effect of the secondary task tended to be larger in the Blocked only and the Random only conditions than in the remaining two learning conditions, especially for the short duration trials. To increase statistical power, and to test the hypothesis that mixed practice schedules lead to better learning outcomes than a pure schedule (i.e., when either Blocked or Random practice is introduced alone), the four groups of participants were re-categorized into two, with Blocked only and Random only learners being considered as a *Homogeneous* group, and the remaining two learning groups (mixed schedule groups) as a *Heterogeneous* group. Consequently, an additional 2 (Homogeneity) x 2 (Testing Condition) x 2 (Target Duration) ANOVA was conducted to examine whether the effect of secondary task would be moderated by the homogeneity of practice schedule. A significant three-way interaction effect was observed, $\Lambda = 0.86$, $F(1, 38) = 6.04$, $p = 0.019$. No other significant results were obtained (Fs ≤ 2, ps ≥ 0.16). To deconstruct the interaction, separate Testing Condition x Target Duration ANOVAs were conducted for each of the recategorized groups. For the Homogeneous group, the main effect of Testing Condition was significant, $\Lambda = 0.8$, $F(1, 19) = 4.8$, $p = 0.042$, indicating greater RMSE when the secondary task was imposed (560±471 ms) than when it was not imposed (436±260 ms). The effect of Target Duration was not significant, $F < 1$. However, the Testing Condition x Target Duration interaction was significant, $\Lambda = 0.71$, $F(1, 19) = 7.8$, $p = 0.011$. Subsequent paired sample t-tests with Bonferroni correction showed that there was an increase in RMSE with the inclusion of the secondary task but such an effect was significant only in the short duration trials, $t(19) = 3.4$, $p = 0.003$, not in the long duration trials, $t(19) < 1$, $p = 0.39$. For the Heterogeneous group, however, neither the main effects of Testing Condition and Target Duration, nor the interaction was significant (Fs ≤ 2.3, ps ≥ 0.14). The RMSE of the participants' utterance durations in the various conditions are shown in Figure 5.

[Insert Figure 5 about here]

Mean duration difference analysis. Apart from the RMSE analysis, a separate ANOVA was conducted to investigate the effects of Learning Condition and Testing Condition on the duration difference between short and long duration trials. A significant main effect of Testing Condition was found, $\Lambda = 0.82$, $F(1, 36) = 7.9$, $p = 0.008$, indicating that the difference in utterance duration between the two targets was smaller when the secondary task was imposed than when it was not imposed (784±340 ms in the transfer test vs. 852±340 ms in the 2nd retention test). No other significant results were obtained (Fs ≤ 2.4, ps ≥ 0.1).

Key Pressing Task

Each participant completed the same key pressing task (with 16 trials) twice, first in the pre-test, and second in the transfer test. Incorrect responses (1.3% of the original data) were excluded from subsequent reaction time analyses. A two-way ANOVA was conducted to evaluate the effect of testing situation and learning condition on participants' performance in the key pressing task. The dependent variable was mean response time (in ms). The between subjects-factor was Learning Condition with four levels and the within-subjects factor was Testing Condition with two levels (Pre-test vs. Transfer test). The main effect of Testing Condition was significant, $\Lambda = 0.54$, $F(1, 36) = 30.9$, $p < 0.001$, indicating that participants' response times were shorter in the pre-test (Mean = 589±92 ms) than in the transfer test (Mean = 755±217 ms). However, neither the main effect of Learning Condition nor the interaction effect reached significance (Fs < 1.6, ps > 0.2). Participants' mean response times and error rates in the various conditions are shown in Table 2.

[Insert Table 2 about here]

Additional Analyses

Additional analyses were performed to examine the strategy adopted by participants in completing the speech task. For instance, the utterance duration can be lengthened by inserting pauses in-between syllables or by slowing down the overall speech rate. To address this issue, the proportion of voiced segments (PVS) within an utterance (in %) was measured using Praat software (Boersma & Weenink, 2008). The higher the PVS, the higher the number of voiced components within the utterance, and vice versa. Specifically, for each participant, the PVS of the three pre-test trials were averaged to form the baseline. Similarly, the mean PVS of the last three short-duration trials and the last three long-duration trials during acquisition were calculated. If a pause-insertion strategy was adopted, a significant decrease in PVS (since pauses are unvoiced segments) would be expected between pre- and late-acquisition phases. Alternatively, if participants slowed down their overall speech rate during acquisition, a comparable PVS would be expected (since the ratio between voiced and unvoiced components was kept approximately constant throughout the acquisition phase).

Consequently, a 4 (Learning Condition) x 3 (Trial Type: Pre-acquisition Trials, Late-acquisition Short-duration Trials, and Late-acquisition Long-duration Trials) ANOVA with repeated measures was conducted to examine participants' mean PVS values in various learning and trial conditions. No significant effects were observed (all Fs < 1), indicating that the mean PVSs were comparable across groups and trial conditions. Participants' mean PVS values in various conditions are presented in Table 3.

[Insert Table 3 about here]

Discussion

Past research on limb motor learning has shown that, relative to random practice, blocked practice promotes better performance in acquisition but poorer performance in retention or transfer tests (Shea & Morgan, 1979). Furthermore, there is evidence to suggest that a mixed practice schedule is more effective than either blocked or random practice alone (Porter & Magill, 2010). The present study was designed to investigate whether a similar pattern of results can be observed in the context of speech motor learning by using an utterance duration control task (Adams & Page, 2000).

In addition, previous studies employing a similar utterance duration control task did not report what strategy participants used in achieving the target utterance duration (e.g., Adams & Page, 2000). By measuring the PVS of participants' utterances in both pre- and late-acquisition trials, the present results suggest that participants in all four learning conditions were slowing down their overall speech rate, but not artificially inserting pauses in-between syllables, when completing the task.

Effects of Practice Schedules

The results of this speech motor learning study are in general consistent with those commonly reported in the literature of limb motor learning. Although no significant difference in RMSE of utterance duration was observed between Blocked only and Random only conditions in either acquisition or retention of the target, a difference between blocked and random practice was indirectly shown in other aspects of the results. For instance, participants' performance in the first practice block did not differ across groups but significant group differences were evident in the second practice block. In the second practice block, participants who received blocked practice in the first two blocks (i.e., Blocked only and Blocked-then-Random learners) showed a reliably lower RMSE than those who received random practice in the first two blocks (i.e., Random only and Random-then-Blocked learners). Similarly, but only to a marginally significant extent, participants from the Blocked only condition showed a lower RMSE than those from the Random only and Blocked-then-Random conditions in the third practice block (Figure 1). These results are in line with the findings from previous limb motor learning research that blocked practice leads to better performance than random practice during acquisition (Brady, 1998; Lee & Simon, 2004; Shea & Morgan, 1979). Furthermore, regarding the participants' performance in the two retention tests, the mean difference in utterance duration between the two target durations was significantly smaller in the Blocked only condition (i.e., 602 ms; where 1000 ms was ideal) than that in the Random only condition (969 ms). This result suggests that, relative to Random only learners, Blocked only learners were less able to differentiate the two utterance durations during the retention tests, consistent with the general findings from limb motor learning literature that random practice leads to better performance than blocked practice in retention (Brady, 1998; Lee & Simon, 2004; Shea & Morgan, 1979).

More importantly, similar to the findings of Porter and Magill (2010), the present results suggest that mixed practice schedules produced more desirable learning outcomes than either blocked or random practice alone. Specifically, our results show clearly that learners who received mixed practice schedules were better able to resist the adverse effects of a concurrent secondary task upon speech (i.e., a sign of automaticity) than those who received a pure blocked or random practice schedule, at least in short duration trials. The superiority of mixed schedules was more prominent in short-duration trials, probably due to the fact that the temporal overlap between primary and secondary tasks was more serious in short-duration trials than in long-duration trials hence resulting in greater attentional conflict and costs for the primary speech task. Note that the focus of Porter and Magill (2010) was on limb motor learning whereas the focus of the present study is speech motor learning; the consistent findings across these two lines of research indicate that some common principles of skill acquisition might be at work with both limb motor and speech motor learning.

Explanations for the Practice Schedule Effects on Speech Motor Learning

Traditional theories of motor control and learning, such as the Schema Theory, have made a distinction between a generalized motor program (GMP) and a parameter (Schmidt, 1975). A GMP represents the relative timing and relative force of the muscle commands necessary for performing a specific class of movements, whereas the parameters assigned for a given GMP specify the absolute timing and absolute force of muscle activities in the target effectors. The construction of GMPs and the specification of parameters are conducted and refined during skill acquisition. The distinction between GMP and parameter, as assumed by the Schema Theory, is analogous to the distinction between core motor plan and motor plan adaptation postulated by the Four-level Framework of speech motor control discussed in the Introduction. With reference to the utterance duration control task used in the present study, participants were essentially asked to learn to scale the same speech motor movement (i.e., the same utterance) along the time dimension. In other words, participants learnt to execute the same GMP or core motor plan but to assign two specific sets of parameters or adaptations (absolute timings for 2500-ms and 3500-ms utterances) during speech motor planning.

The retention benefits of Random only practice over Blocked only practice observed in the present study can be explained by the three proposed accounts described in the Introduction. For instance, according to the elaboration hypothesis (Shea & Morgan, 1979; Shea & Zimny, 1983), random practice may have fostered a more elaborated, distinctive memory representation of the different parameter settings, and hence Random only learners were better able to differentiate the two target outputs (i.e., 2500-ms and 3500-ms utterances) than Blocked only learners during retention. However, the elaboration hypothesis poorly explains the mixed schedule advantage reported here. The hypothesis holds that the locus of the practice schedule effects is situated at the level of motor memory representation, and the best way to achieve optimal memory representations is to compare and contrast different motor skills within the same block. Accordingly, Random only learners should have achieved the best learning outcomes in the present study as the possibilities for comparing and contrasting the two motor plans were maximized. However, a mixed schedule advantage was observed, indicating that the present results cannot be fully accounted for by the elaboration hypothesis alone.

A novel finding of this study relates to the two mixed schedule conditions (i.e., Blocked-then-Random and Random-then-Blocked conditions). Although the participants from these two conditions showed different patterns of performance during acquisition, their performance in retention and transfer tests was highly comparable. These results suggest that the mixed schedule advantage observed was not dependent on the presentation order of the types of practice included in acquisition, but was due to the variety of practice schedules. Note that this finding might not easily be accommodated by theories that have previously been proposed to explain the mixed schedule advantage (e.g., Boyce et al., 2006; Guadagnoli & Lee, 2004). This is because the mixed practice schedules studied in the past were almost all of a Blocked-then-Random type; the effect of Random-then-Blocked practice has rarely been studied. Theories such as the challenge-point hypothesis (Guadagnoli & Lee, 2004) emphasize a continuous match between the skill level of the learner and the difficulty level of the task as the acquisition phase proceeds. Accordingly, the most optimal practice schedule should be one that includes initial blocked practice and ends with random practice. Note that the Random-then-Blocked condition is actually in complete contrast to such a proposal. However, comparable learning outcomes were observed across the Blocked-then-Random and Random-then-Blocked conditions in this study, indicating that it is the variety, and not the presentation order, of the practice schedules that matters.

Nevertheless, both the reconstruction hypothesis and implicit motor learning hypothesis potentially can account for the mixed schedule advantage observed, if additional assumptions are made. According to the reconstruction hypothesis (Lee et al., 1985; Lee & Magill, 1983), blocked practice allows learners to buffer most of the motor specifications in working memory during a block such that it is not necessary for learners to re-run the entire speech motor planning process (e.g., the various phases within the Four-level Framework of speech motor control, see Van der Merwe, 1997) across trials. In contrast, random learners need to reconstruct the speech motor plan (including the specific parameter settings) across trials. Consequently, random learners gain more practice of motor plan construction and parameter assignment via repeated reconstruction. However, such a proposal does not preclude the possibility that practicing to hold motor details in working memory and to maintain invariant motor outputs across trials (as promoted in blocked practice) is also beneficial to skill learning, albeit perhaps to a lesser extent than practicing to renew the motor plan repeatedly (as encouraged in random practice). As suggested by Landin and Hebert (1997), the optimal practice schedule might be one that includes the best features of blocked and random practice. Consequently, the amount of learning is greater when these two types of practice are both adopted than when either type of processing is emphasized alone. Further research is needed to verify these hypotheses.

The second possible account comes from the literature on implicit motor learning and, more specifically, recent evidence suggesting a link between practice schedule and implicit motor learning (Rendell et al., 2009; 2010). For instance, Rendell et al. (2010) asked their participants to learn two Australian Rules Football tasks (kicking and handball) in either a random or a blocked practice condition, and found that random learners outperformed blocked learners in a secondary transfer task, although the difference was restricted to the more complex kicking task. More importantly, random learners verbally reported a smaller amount of movement-related knowledge than blocked learners at the end of acquisition. The authors argued that it was the cognitive load due to task-switching that prevented random learners from testing hypotheses and accumulating movement-related verbal rules during acquisition, hence resulting in a more implicit mode of skill learning (see Masters, 1992; Masters & Maxwell, 2008; Masters & Poolton, 2012, for in-depth discussions of the principles of implicit motor learning). However, Rendell et al. (2010) did not include a mixed schedule condition in their study so it remained open whether a switch in practice schedule (as occurred in the two mixed schedule conditions in the present study) would further increase the cognitive load of the learner (because of the need to accommodate a novel practice schedule), and hence result in an even more implicit mode of learning. If it is the case that a mixed practice schedule is cognitively more demanding than a pure one, then one would expect superior learning in mixed compared with pure practice schedule conditions. However, whether the mixed schedule advantage observed in the present study has its root in implicit motor learning warrants further investigation.

Clinical Implications and Conclusions

While it is not yet clear why comparable learning outcomes were found in the two mixed schedule conditions in this study, the present results do show clearly that mixed practice schedules are more effective than pure blocked or pure random practice, especially in transferring the acquired motor skills to novel environments. The resistance to the detrimental effects of the secondary task demonstrated by the learners from the two mixed schedule conditions indicates automaticity in performing the primary speech task. Note that such findings have important implications for the clinical setting where random practice (and random practice alone) has long been considered to be the optimal learning condition (e.g., Adams & Page, 2000; Ballard, Robin, McCabe, & McDonald, 2010; Knock et al., 2000; Maas & Farinella, 2012; Smith, Sadagopan, Walsh, & Weber-Fox, 2010). However, further research is needed to examine whether the mixed schedule advantage observed in this study can be generalized to individuals with speech impairments, as well as to other aspects of speech (e.g., pitch variation, speech loudness, voice quality), or other transfer situations (e.g., controlling the duration of a novel non-practiced utterance). Furthermore, as discussed above, the speech task employed in this study focused mostly on parameter adjustment; whether or not the same mixed schedule advantage can be observed in the learning of speech-related GMPs or core speech motor plans is still unknown. Indeed, previous studies on limb motor learning have shown differential effects of practice schedule for GMP and parameter processing (e.g., Wright & Shea, 2001). Similarly, future investigation is needed to identify the locus of the practice schedule effects along the various phases of speech motor control (Van der Merwe, 1997). A better understanding of this will help clinicians decide which particular practice schedule is most suitable for a client with a given speech motor disorder. Lastly, although the findings of this speech motor learning study are in general consistent with those obtained in limb motor learning research, it is not self-evident that all principles of limb motor learning can automatically be applied to the speech domain (Maas et al., 2008). Future research is needed to investigate the universality of the motor learning principles developed primarily from a non-speech domain.

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Table 1

Mean difference in duration (ms) between short and long utterances across testing and learning conditions

Learning Condition	Retention 1	Retention 2	Transfer
Blocked only	595 (235)	608 (359)	614 (379)
Random only	968 (136)	970 (225)	826 (187)
Blocked-then-Random	865 (283)	1008 (292)	915 (372)
Random-then-Blocked	724 (293)	820 (357)	780 (362)

Note: Standard deviation in parentheses

Table 2

Participants' mean response time (RT; in ms) and error rate (Err; in %) in the key pressing task across testing and learning conditions

Learning Condition	Pre-test		Transfer test	
	RT	Err	RT	Err
Blocked only	574 (44)	1.9 (3.1)	849 (294)	1.3 (2.7)
Random only	580 (85)	0.7 (2)	702 (117)	0.7 (2)
Blocked-then-Random	592 (115)	1.3 (2.7)	752 (248)	0 (0)
Random-then-Blocked	609 (116)	4.4 (5.2)	718 (167)	0.7 (2)

Note: Standard deviation in parentheses

Table 3

Mean Proportion of Voiced Segments (PVS; in %) during participants' utterances in the pre-test and late acquisition phases

Learning Condition	Pre-test	Late-acquisition Short-duration trials	Late-acquisition Long-duration trials
Blocked only	67.7 (9.5)	68.7 (11.4)	67.8 (14.4)
Random only	71.3 (12.1)	70.4 (11.3)	70.8 (14.7)
Blocked-then-Random	72.1 (9.9)	72 (9.6)	69.4 (13.1)
Random-then-Blocked	72.2 (10.5)	72.2 (13.6)	71.2 (13)

Note: Standard deviation (%) in parentheses

Figure Captions

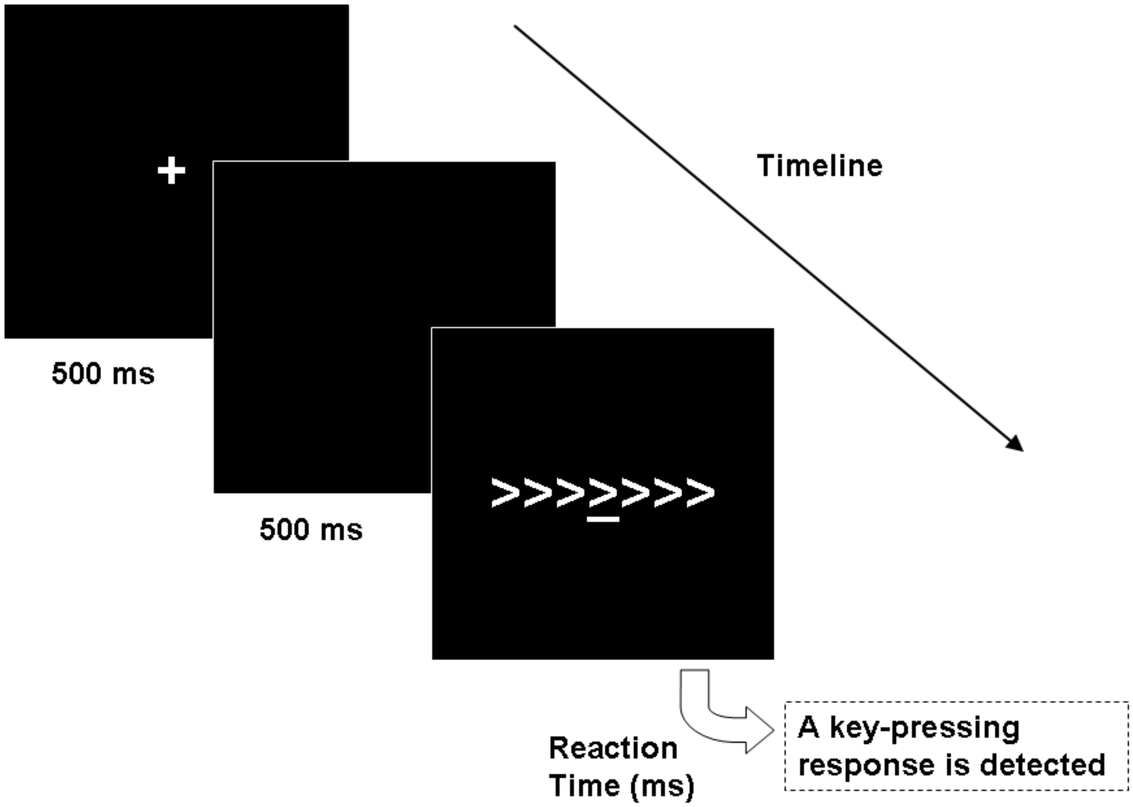
Figure 1. A schematic layout of the trial procedure for the secondary key-pressing task.

Figure 2. Changes in Root Mean Square Error (RMSE) of participants' utterance durations during the acquisition phase as a function of target duration and learning condition. The diamonds represent the Blocked only condition, the squares represent the Random only condition, the triangles represent the Blocked-then-Random condition, and the crosses represent the Random-then-Blocked condition.

Figure 3. The Root Mean Square Error (RMSE) of participants' utterance durations in the two retention tests as a function of target duration and learning condition.

Figure 4. The Root Mean Square Error (RMSE) of participants' utterance durations in the delayed retention test and transfer test as a function of target duration and learning condition.

Figure 5. The Root Mean Square Error (RMSE) of participants' utterance durations in the delayed retention test and transfer test as a function of target duration and homogeneity.



500 ms
500 ms
>>>≥>>>>
Timeline
Reaction Time (ms)
A key-pressing response is detected

Figure 1.

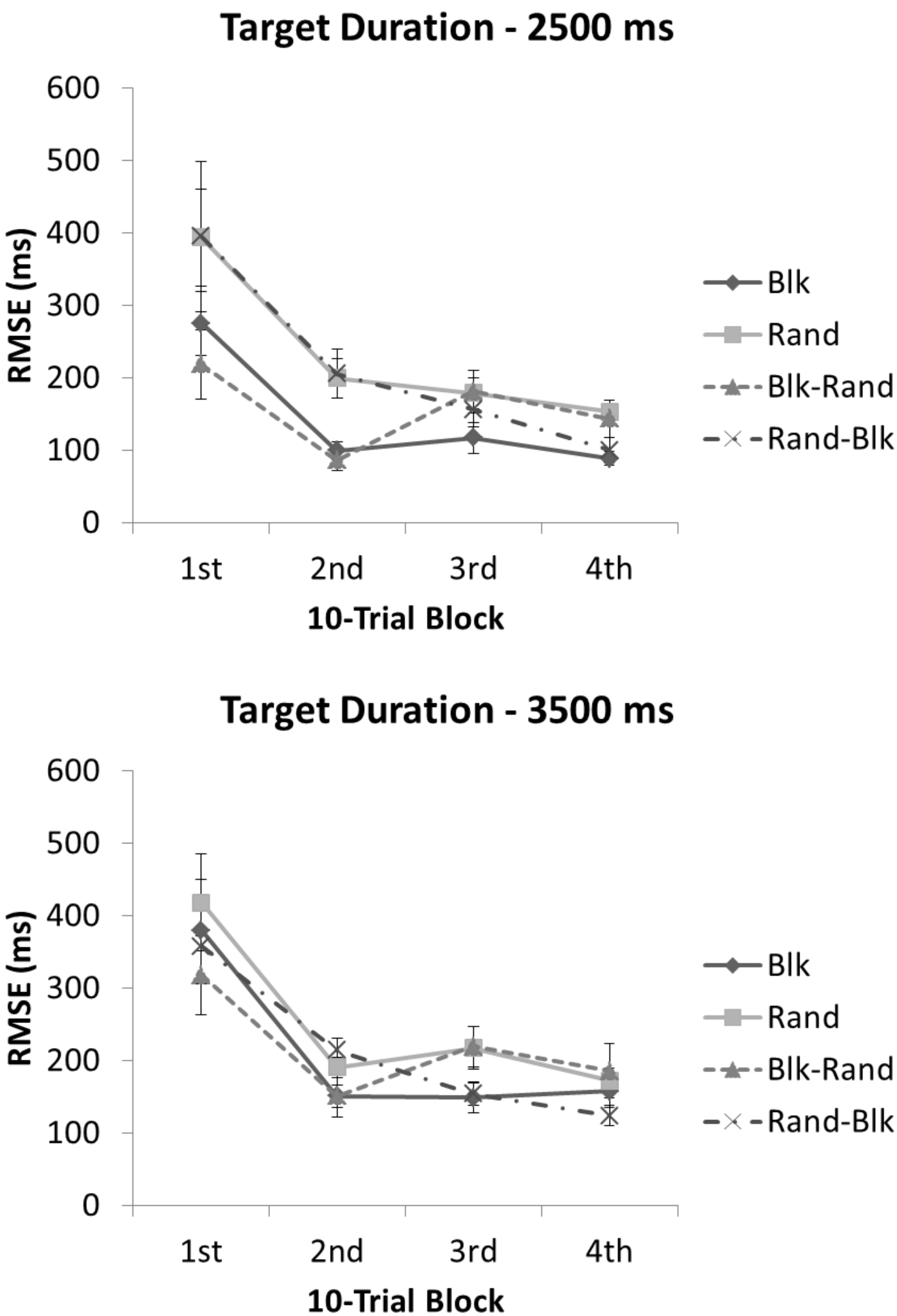

Target Duration - 2500 ms
600
500
400
300
200
100
0
RMSE (ms)
1st
2nd
3rd
4th
10-Trial Block
Blk
Rand
Blk-Rand
Rand-Blk
Target Duration - 3500 ms
600
500
400
300
200
100
0
RMSE (ms)
1st
2nd
3rd
4th
10-Trial Block
Blk
Rand
Blk-Rand
Rand-Blk

Figure 2.

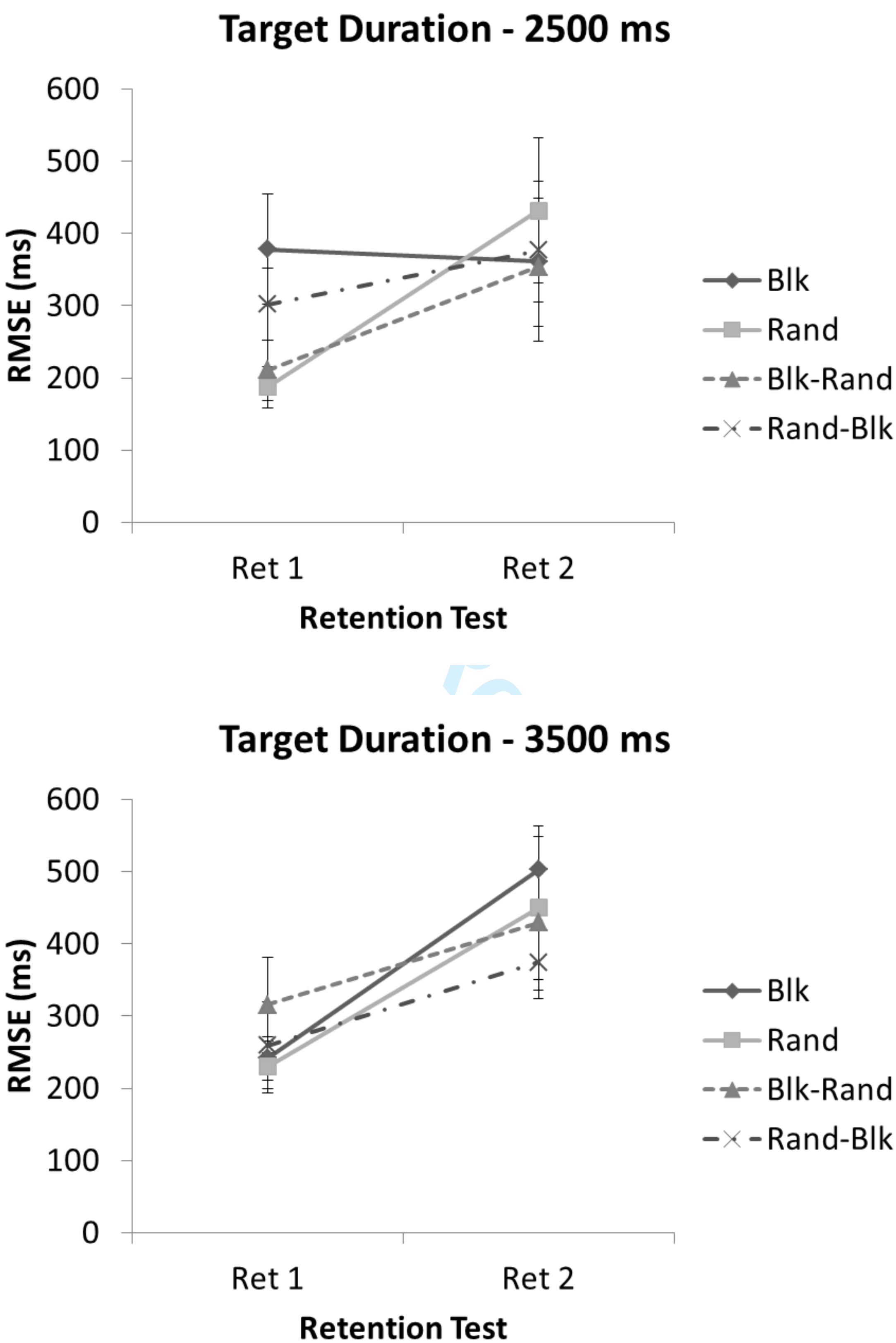
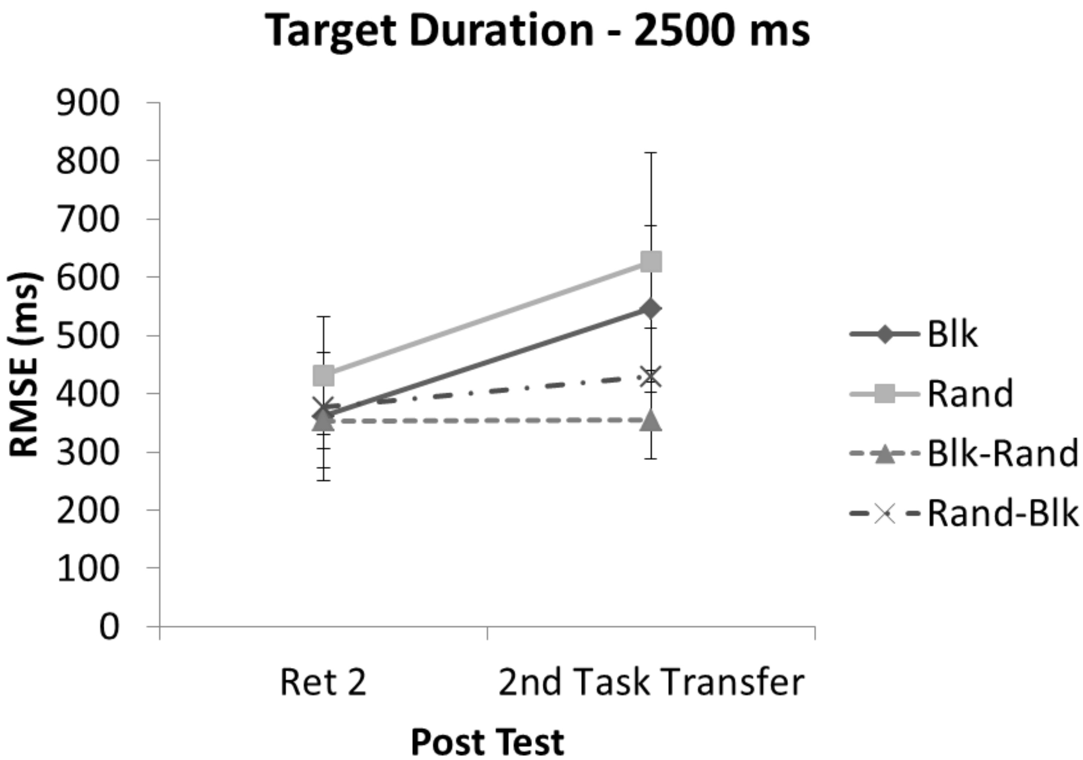
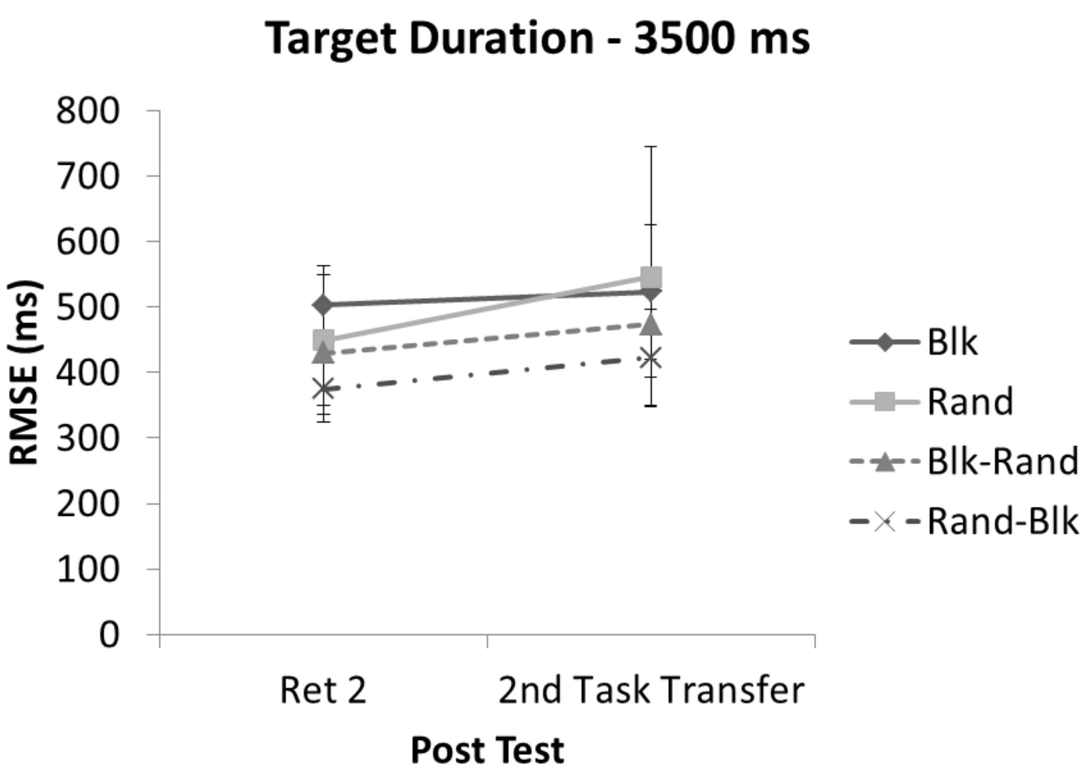

Target Duration - 2500 ms
600
500
400
300
200
100
0
RMSE (ms)
Ret 1
Ret 2
Retention Test
Blk
Rand
Blk-Rand
Rand-Blk
Target Duration - 3500 ms
600
500
400
300
200
100
0
RMSE (ms)
Ret 1
Ret 2
Retention Test
Blk
Rand
Blk-Rand
Rand-Blk

Figure 3.

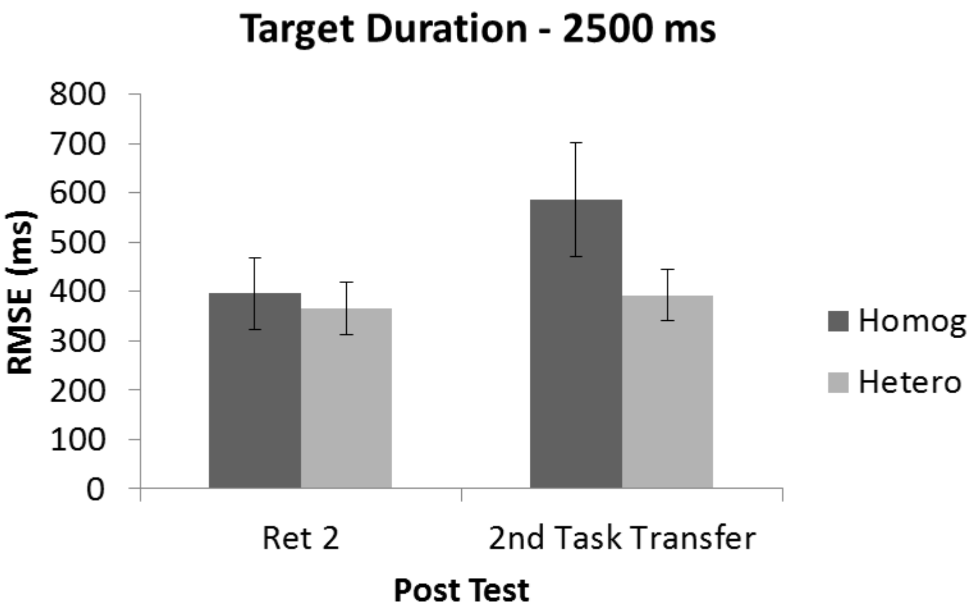


Target Duration - 2500 ms
900
800
700
600
500
400
300
200
100
0
RMSE (ms)
Ret 2
2nd Task Transfer
Post Test
Blk
Rand
Blk-Rand
Rand-Blk



Target Duration - 3500 ms
800
700
600
500
400
300
200
100
0
RMSE (ms)
Ret 2
2nd Task Transfer
Post Test
Blk
Rand
Blk-Rand
Rand-Blk

Figure 4.


Target Duration - 2500 ms
800
700
600
500
400
300
200
100
0
RMSE (ms)
Ret 2
2nd Task Transfer
Post Test
Homog
Hetero

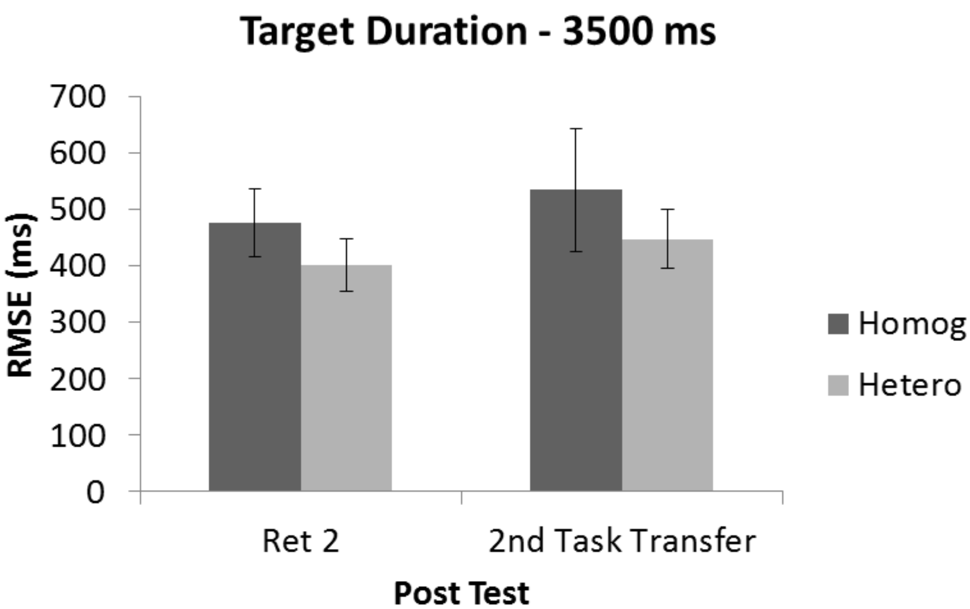

Target Duration - 3500 ms
700
600
500
400
300
200
100
0
RMSE (ms)
Ret 2
2nd Task Transfer
Post Test
Homog
Hetero

Figure 5.