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RESEARCH ARTICLE

Dual-task practice enhances motor learning: a preliminary investigation

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Abstract Practicing a motor task under dual-task conditions can be beneficial to motor learning when the secondary task is difficult (Roche et al. in Percept Psychophys 69(4):513–522, 2007) or when it engages similar processes as the primary motor task (Hemond et al. in J Neurosci 30(2):650–654, 2010). The purpose of this pilot study was to determine which factor, difficulty level or engaged processes, of a secondary task is more critical in determining dual-task benefit. Participants practiced a discrete arm task in conjunction with an audio-vocal reaction time (RT) task. We presented two different RT tasks that differed in difficulty, simple versus choice (i.e., more difficult), at two different arm task phases that differed in engaged processes, preparation versus execution, resulting in four dual-task conditions. A simple RT task is thought to predominantly engage motor execution processes, therefore would engage similar processes as the arm movement task when it is presented during the execution phase, while a choice RT task is thought to engage planning processes and therefore would engage similar processes too when it is presented during the preparation phase. Enhanced motor learning was found in those who engaged similar process as the primary task during dual-tasking (i.e., choice RT presented during preparation and simple RT presented during execution). Moreover, those who showed enhanced learning also demonstrated high dual-task cost (poor RT task performance) during practice, indicating that both tasks were taxing the same resource pool possibly due to engaging similar cognitive processes. To further test the relation between dual-task cost and enhanced learning, we delayed the presentation timing of the choice RT task during the preparation phase and the simple RT task during the execution phase in two control experiments. Dual-task cost was reduced in these delayed timing conditions, and the enhanced learning effect was attenuated. Together, our preliminary findings suggest that it is the similarity hypothesis and not the difficulty hypothesis that mediates the enhanced motor learning under dual-task conditions.

Keywords Dual-task · Interference · Attention · Resource · Skill acquisition

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Introduction

Dual-tasking plays a critical role in human daily activities such that it has become a focus of research among behavioral neuroscientists. In particular, considerable work has been done to understand how dual-tasking can influence performance and learning of motor skills. While most studies report that performance or learning of a motor skill under dual-task conditions is detrimental (Schumacher and

Schwarb 2009; Hiraga et al. 2009; Chong et al. 2010), two recent studies suggest the opposite (Roche et al. 2007; Hemond et al. 2010). This highlights our limited understanding of dual-task behaviors and challenges a long-held belief that dual-tasking is generally detrimental.

Roche et al. (2007) found that learning of a perceptual-motor task was facilitated when practice was paired with a difficult secondary task but not when practice was paired with an easy secondary task. The authors suggested that the difficult, as opposed to easy, secondary task induced a positive vigilance effect that was beneficial for primary task performance measured at delayed retention. In other words, it may be that participants increased the use of attentional resources when handling a difficult secondary task. Increased cognitive effort during practice is a well-recognized factor that benefits motor learning (Lee et al. 1994). For example, Li and Wright (2000) reported that a random practice schedule (multiple tasks practiced in an interleaved order), compared to a blocked practice schedule (tasks practiced in a sequential order), led to greater attentional cost (i.e., greater cognitive effort) but better retention performance, as measured 1 day after practice (Li and Wright 2000). Thus, it is possible that a difficult secondary task imposes additional cognitive demands on the learner, which in turn enhances the encoding of the primary task.

Hemond et al. (2010) reported that performance of a finger sequence task was enhanced in participants who were instructed to simultaneously search for a visual color sequence during practice. In contrast, finger task performance was impaired when participants were instructed to simultaneously count the frequency of a particular color cue. The authors argued that it is the concurrent engagement of similar "sequence" processes, instead of amount or complexity of information load that enhances the primary task performance at the end of practice. This argument is in line with Wicken's multiple attentional resource model (Wickens 2002). In Wicken's model, the attentional system is conceptualized having multiple pools of resources, and each resource pool handles specific processes. Two tasks will tax the same resource pool if they engage similar processes and are performed at the same time. Hemond et al. hypothesized that the benefit they observed may due to facilitated activation of a sequence-related neural circuitry when that circuitry is already engaged. The secondary task that engages similar processes as the primary task may facilitate the engagement of the important network and in turn enhance primary task performance. However, there was no delayed retention test given in Hemond et al.'s study. Thus, it is unclear whether a similar benefit would extend to post-practice retention performance where *learning* is considered to be more reliably represented (Cahill et al. 2001).

Here, we asked which factor, task difficulty or concurrent engagement of similar processes, is more critical in modulating the dual-task practice benefits on primary task learning as measured by delayed retention performance. We used a simple and a two-choice audio-vocal reaction time (RT) task as the secondary tasks. These two tasks are different in their difficulty levels and engaged processes (Klapp 1996). A simple RT task with a motor response engages primary motor cortex right after stimulus identification (Kumru et al. 2008; Hashimoto et al. 2004), possibly for response generation and execution. Based on a serial information processing model (Miller and Low 2001), a choice RT task engages motoric (response execution) processes much later in time after stimulus onset compared to a simple RT task, presumably after stimulus identification and response selection processes are completed or nearly completed. Thus, a choice RT task usually results in a longer response time and is considered more difficult than a simple RT task because it additionally engages response selection processes that are only minimally, if at all, engaged in a simple RT task (Miller and Low 2001).

Our primary task was a discrete arm movement task with distinct preparation and execution phases. Evidence suggests that different processes are engaged at different phases of discrete movements (Cross et al. 2007; Fleury et al. 1994). Response planning processes are predominantly engaged during the preparation phase but minimally engaged during the execution phase (Mirabella et al. 2008). Thus, using this unique design with two levels of secondary task difficulty and two levels of primary task movement phase, we can begin to isolate which of the two factors is more important in implementing the dual-task benefits on motor learning. We presented the two types of RT tasks at two different movement phases. Within the same movement phase, the choice RT task results in a more difficult dual-task practice condition compared to the simple RT task. Concurrent engagement of similar processes occurs when the choice RT is presented during movement preparation because both tasks are engaging similar planning processes. Similarly, the simple RT task presented during movement execution phase will result in concurrent engagement of execution processes because both require generation of a motor response.

If, based on Roche et al., secondary task difficulty is critical (i.e., difficulty hypothesis), we predict that (1) the choice RT task will facilitate learning when it is presented during either preparation or execution phases compared to the simple RT task presented at the same movement phase and (2) the choice RT presented during the preparation phase will facilitate learning compared to simple RT task presented during execution phase even though both dual-task conditions result in engagement of similar processes. In contrast, if concurrent engagement of similar cognitive processes is critical (i.e., similarity hypothesis), we predict that (1) the choice RT task will facilitate learning only when it is presented in the preparation but not in the execution phase and (2) the simple RT task will facilitate learning only when it is presented in the execution but not preparation phase.

Materials and methods

Participants

Fifty young healthy adults (mean age, 28 ± 4 years; 28 females and 22 males) were tested. All participants had normal or corrected-to-normal vision and hearing and were clear from any neurological and orthopedic deficits. All participants were naïve to the task and unaware of the hypotheses of the study. All participants, except one, were right-hand dominant as determined by Edinburgh handedness inventory (Oldfield 1971).

Tasks

The primary motor task was a goal-directed discrete arm movement that consisted of two forearm extension-flexion reversal actions, each with a specific amplitude and temporal constraint (Fig. 1a). The target trajectory is the summation of two sine waves: $y(t) = 42\sin(\pi t - 0.3) + 23\sin(3\pi t + 0.4)$. The designated total movement time was 900 ms. During testing, each participant sat in front of a computer monitor with his or her dominant arm resting on a lightweight lever that was attached to a table. This lever was affixed to a nearly frictionless vertical axle such that the lever movement was restricted to the horizontal plane above the surface of the table (Fig. 1b). Figure 1c shows the time events in a typical trial. At the beginning of each trial, the target trajectory was displayed on the computer screen for 1 s, followed by "Ready" and "Go" signals (1 s apart). Participants were instructed to initiate the movement upon the "Go" signal. The task preparation phase was defined as the duration between the "Ready" and "Go" signals, while the execution phase started from the movement onset until the end of the movement (i.e., movement offset). Two seconds after the movement ended, post-response augmented feedback was displayed on the computer screen for 5 s and consisted of an overall numeric error score (root mean squared error, RMSE, calculated after onset synchronization) and a graphic representation of the participant's generated trajectory superimposed on the target trajectory. The goal of this task was to replicate the target trajectory as closely as possible in order to reduce RMSE. Participants practiced the same target trajectory throughout the experiment.

The secondary task was an audio-vocal RT task where participants responded vocally to an audio stimulus. The audio stimulus (1,000 or 500-Hz tone) was played to

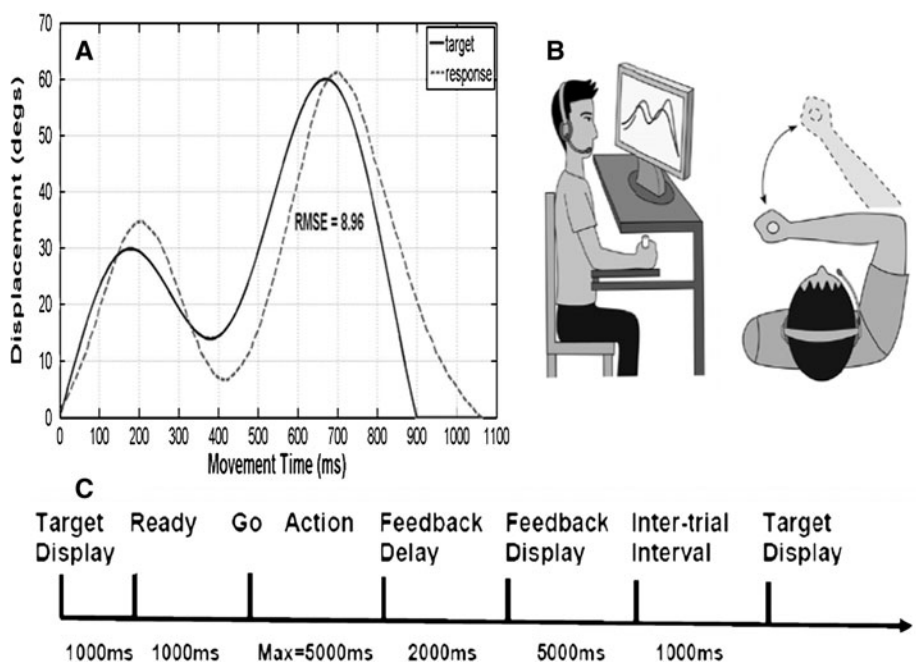

Fig. 1 **a** Target movement (*target*) with specific movement time (*ms*) and angular displacement (*degrees*) requirements and task performance (*response*) from a typical practice trial of a representative participant. The difference between the target and the participant's performance resulted in a RMSE of 8.96. **b** Participant sat in front of a computer with right arm rested on the lever (*side view*). The movement consisted of forearm extension and flexion actions with elbow as rotational axis (*top down view*). **c** Temporal events in a typical practice trial. Depending on group assignment, participants heard the audio probe stimuli during either preparation phase (between *Ready* and *Go*) or execution phase (*Action*)

participants via headphones, and participant's vocal response was recorded by a microphone (Fig. 1b). There were two different types of secondary tasks, simple and choice RT tasks. In the simple RT task, participants heard the 1,000-Hz tone and responded as soon as possible by saying "High" into the microphone. In the choice RT task, participants responded to one of the two possible audio stimuli (1,000 or 500-Hz tone) by saying "High" or "Low" correspondingly. The tone was synchronized to the primary motor task by a customized LabView-based program and presented during either the preparation (50 ms after the "Ready" signal) or execution (300 ms after movement onset) phase of the primary task. These probe latencies were selected based on the previous studies and our own pilot work showing that the processing demands were high during relatively "early" task preparation and execution phases. Thus, we expected to detect measurable behavioral changes by probing participants using these specific probe latencies.

Design and procedure

Participants were randomly and equally assigned to groups based on secondary task type (Choice, Simple) and primary task movement phase (Preparation, Execution). Thus, there were four experimental groups: Choice-Preparation, Simple-Preparation, Choice-Execution, and Simple-Execution. Choice-Preparation and Choice-Execution groups practiced under dual-task conditions with a more difficult secondary task compared to Simple-Preparation and Simple-Execution groups, respectively. The Choice-Preparation and Simple-Execution groups engaged similar processes as the primary task during dual-tasking, while Choice-Execution and Simple-Preparation did not. The control group included participants who practiced the primary motor task without a secondary task and were designated as the Control-NoProbe group.

The experiment took place over 3 consecutive days. On Day 1 and Day 2, participants received three 48-trial blocks of practice for a total of 144 practice trials per day. Post-response augmented feedback was presented after every trial during practice. For the experimental groups, the secondary task was presented on 8 out of the 48 trials in each practice block (probe trial frequency $\approx$17 %). To reduce the anticipation of the secondary task, the probe trial was pseudo-randomly placed every 5–7 practice trials. Participants were instructed to respond to the audio stimulus as soon as possible with task priority emphasized on the primary task. Participants received different types of secondary tasks (simple or choice RT) at different phases of the primary task (preparation or execution) on the probe trials based on their group assignment. We specifically adopted a low probe frequency (17 %) and primary task prioritization to avoid simultaneous learning of the secondary task. Hemond et al. (2010) suggested that concurrent engagement of "learning" processes may also contribute to dual-task practice benefits. Our design minimized the likelihood of engaging "learning" processes concurrently.

Participants' retention performance on the primary task was measured at immediate and delayed retention tests. The immediate retention test was administered at the end of Day 1 and Day 2, immediately after each practice phase. The delayed retention test was administered at the beginning of Day 2 and Day 3, approximately 24 h following each practice phase. On each retention test, participants performed 12 trials of the primary task without augmented feedback or the secondary task.

In addition, we measured each participant's baseline RT under single-task condition at the beginning of each day. During testing, each participant sat on a chair wearing headphones and a microphone *without* performing any arm movement. We measured simple and choice RT under single-task condition on every participant. For those in the Simple-Preparation and Simple-Execution groups, simple RT measured under single-task condition served as their baseline; choice RT measured under single-task condition served as the baseline for Choice-Preparation and Choice-Execution groups. We referenced participant's probe RTs measured during practice to their individual baseline RTs (see "Data analysis" for detail).

Data analysis

The dependent measures included the accuracy of the primary task as measured by RMSE and the reaction time (RT) of the secondary probe task. RMSE (in degrees) was calculated as the difference between the participant's movement response and the target trajectory and reflected both spatial and temporal accuracy of task performance (see Fig. 1a). Reaction time (in ms) was calculated from the onset of the audio stimulus to the onset of the participant's vocal response. Participants made inaccurate verbal responses during performance of the choice RT task. However, the accuracy was generally high (97–98 %) and comparable across groups. We removed the incorrect trials from the analysis.

To assess how well participants learned the primary task, we contrasted participants' arm task performance (RMSE) on delayed retention of Day 3 to the immediate retention of Day 2 with a repeated-measures ANOVA test. This analysis allowed us to compare learning (delayed retention performance on Day 3) among groups while using participants' end-of-practice performance (immediate retention on Day 2) as the reference. Participants' performance on the primary (RMSE) and secondary tasks (RT) during practice was analyzed with a repeated-measures ANOVA test. To compare secondary task performance across groups, we computed dual-task cost by subtracting RT measured under dual-task conditions from RT measured under single-task conditions. A p value less than .05 was considered significant. Least significant difference (LSD) or Dunett's T3 post hoc test was performed if a significant group difference was found. LSD was used when the assumption of equal variance among groups is not violated; otherwise, Dunett's T3 test was used.

Results

Compared to the no probe control condition, the secondary task enhanced primary motor task learning only if the choice RT task was presented in the preparation phase (Fig. 2a CP group, solid circle) or if the simple RT task was presented in the execution phase (Fig. 2a SE group, open triangle). A significant Group × Test interaction ($F_{(4,45)} = 6.24$, $p < .001$) was found by contrasting the immediate and delayed retention tests using a repeated-measures ANOVA (Fig. 2a). Univariate ANOVA tests revealed that the groups were not different at the immediate retention ($F_{(4,45)} = 2.04$, $p = .104$) but were different at the delayed retention ($F_{(4,45)} = 3.94$, $p = .008$). This suggested that the magnitude of change in RMSE across the two retention tests was different among groups.

We then calculated *forgetting* by taking the difference in RMSE between the delayed and immediate retention tests and performed a univariate ANOVA (Fig. 2b). There was a significant group difference in forgetting ($F_{(4,45)} = 6.24$, $p < .001$). To test the difficulty hypothesis, post hoc comparisons revealed the following. (1) Compared to the control, the choice RT task resulted in less forgetting only when it was presented during preparation (Choice-Preparation vs. Control-NoProbe, $p = .01$) but not during execution (Choice-Execution vs. Control-NoProbe, $p = .90$). (2) Within the same movement phase, the Choice-Preparation showed less forgetting than the Simple-Preparation (Choice-Preparation vs. Simple-Preparation, $p = .001$), while the Choice-Execution showed greater forgetting than the Simple-Execution (Choice-Execution vs. Simple-Execution, $p = .004$). (3) For the groups that engage similar processes, the choice RT task (i.e., the difficult task) did not lead to less forgetting than the simple RT task (i.e., the easy task) (Choice-Preparation vs. Simple-Execution, $p = .64$). Based on these findings, our data did not support the difficulty hypothesis. To test the similarity hypothesis, we performed post hoc comparisons and obtained the following results: (1) With the same level of difficulty,

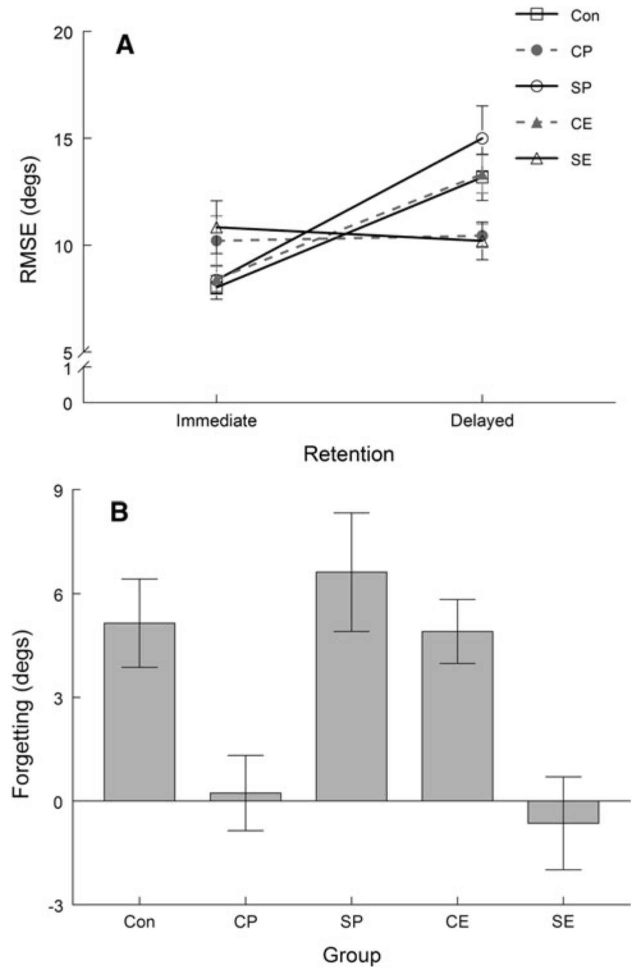

Fig. 2 **a** Participants' arm task performance (RMSE in degrees, mean ± SEM; higher RMSE is indicative of poorer performance) at the immediate (end of Day 2) and delayed (Day 3) retention tests. Changes in performance across the two retentions were different for the Choice-Preparation (*CP*) and Simple-Execution (*SE*) groups compared to the Simple-Preparation (*SP*), Choice-Execution (*CE*), and Control-NoProbe (*Con*) groups. **b** Forgetting (degrees, mean ± SEM) calculated from the difference in RMSE across the two retention tests. The Choice-Preparation (*CP*) and Simple-Execution (*SE*) groups demonstrated minimal forgetting suggesting superior learning, compared to the other groups

Choice-Preparation showed less forgetting than Choice-Execution ($p = .01$), and Simple-Preparation showed more forgetting than Simple-Execution ($p < .001$). (2) Compared to the control, the groups that engaged similar processes showed less forgetting (Choice-Preparation vs. Control-NoProbe, $p = .01$; Simple-Execution vs. Control-NoProbe, $p = .003$). Together, these results provide support for the similarity hypothesis.

We analyzed participants' performance during practice to gain further insights into the enhancement effect we observed during retention. All groups showed similar primary task performance (RMSE) during practice (Fig. 3). This was confirmed by a nonsignificant Group effect

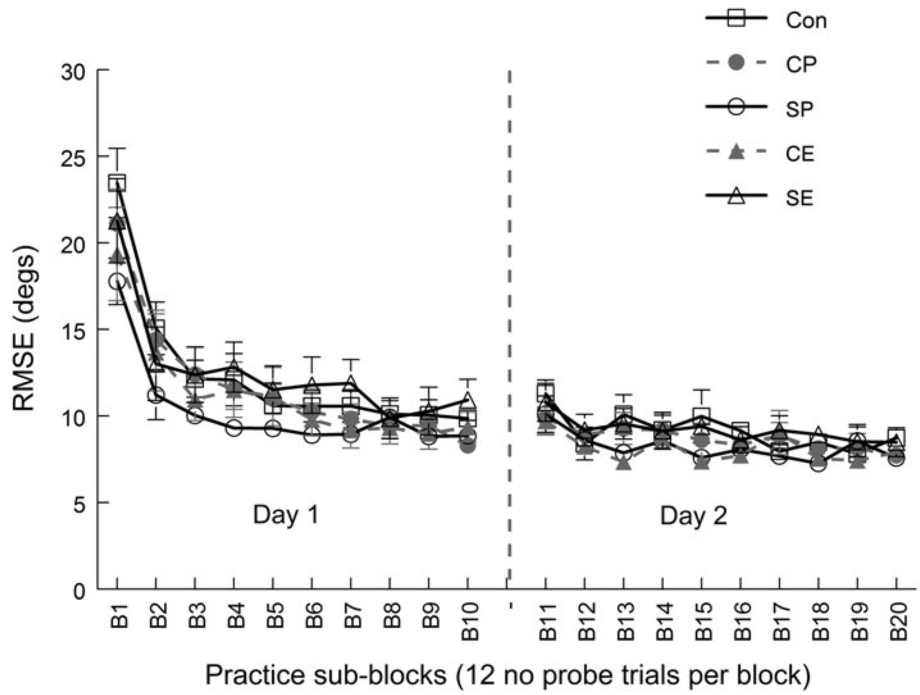

Fig. 3 Participants' arm task performance during practice on Day 1 and 2 (RMSE in degrees, mean ± SEM). Each sub-block consists of 12 no probe trials (performing arm task only). During practice, all groups showed similar arm task performance

($F_{(4,45)} = .83$, $p = .51$) and Group × Block interaction ($F_{(76,836)} = .88$, $p = .63$). The four experimental groups had similar primary task performance on the probe trials as well (Group effect: $F_{(3,36)} = 1.03$, $p = .39$; Group × Block interaction: $F_{(15,180)} = .83$, $p = .57$). Hence, the differences in forgetting among the groups do not seem to be explained by the primary task performance during practice.

In contrast to the primary task performance, secondary task performance (RT) during practice was different among the experimental groups. At the beginning of each day, we measured participants' baseline RTs under a single-task condition (performing RT task only). Consistent with the literature, we showed a significant secondary task type effect at baseline (Fig. 4a) ($F_{(1,36)} = 41.79$, $p < .001$); the simple RTs were significantly shorter than choice RTs. There was no significant Type × Phase interaction at baseline ($F_{(1,36)} = 2.69$, $p = .11$). This suggests that under the single-task condition, the choice RT task is more difficult than the simple RT task. However, RTs measured under the dual-task conditions during practice revealed a significant Type × Phase interaction ($F_{(1,36)} = 8.77$, $p = .01$). Subsequent analysis with adjusted p set at .01 revealed that the Choice-Preparation group had significantly longer probe RTs than the Simple-Preparation group ($p = .003$) and similar probe RTs as the Choice-Execution group ($p = .11$). However, the Simple-Execution group had longer probe RTs than the Simple-Preparation group ($p = .008$) and similar probe RTs as the Choice-Execution group ($p = .74$). The performance of the Simple-Execution group was surprising and suggested a longer delay in the vocal responses in this group compared to their peers. Thus, to compare secondary task performance across groups, we computed *dual-task cost* by subtracting baseline RTs from probe RTs. We also collapsed dual-task cost across practice because there was no significant Practice × Type ($F_{(5,180)} = 1.34$, $p = .25$), Practice × Phase ($F_{(5,180)} = 1.23$, $p = .30$), or Practice × Type × Phase interaction ($F_{(5,180)} = .22$, $p = .95$). Dual-task cost is commonly used to indicate dual-task interference (Ruthruff et al. 2006). Though not statistically significant, the Choice-Preparation group tended to show a higher dual-task cost than the Simple-Preparation group ($p = .08$), while the Simple-Execution group showed a significantly higher dual-task cost than the Choice-Execution group ($p = .04$), resulting in a significant Type × Phase interaction ($F_{(1,36)} = 6.70$, $p = .01$) for dual-task cost (Fig. 4b). The group effects for dual-task cost were not significant (Type: $F_{(1,36)} = .56$, $p = .46$; Phase: $F_{(1,36)} = .91$, $p = .35$). The high dual-task cost found in the Simple-Execution group suggests that the simple RT task and the execution of the arm task may engage similar execution process and tax the same resource pool. This analysis also suggests that those who experienced a greater degree of dual-task interference (i.e., higher cost) during practice (the CP and SE groups) also demonstrated enhanced learning (i.e., less forgetting) in retention.

To test the specificity of enhanced learning from dual-task interference during practice, we recruited two additional control groups, each with a relatively "later" probe latency: Choice-Preparation-Late and Simple-Execution-Late (10 participants per group, 11 females and 9 males;

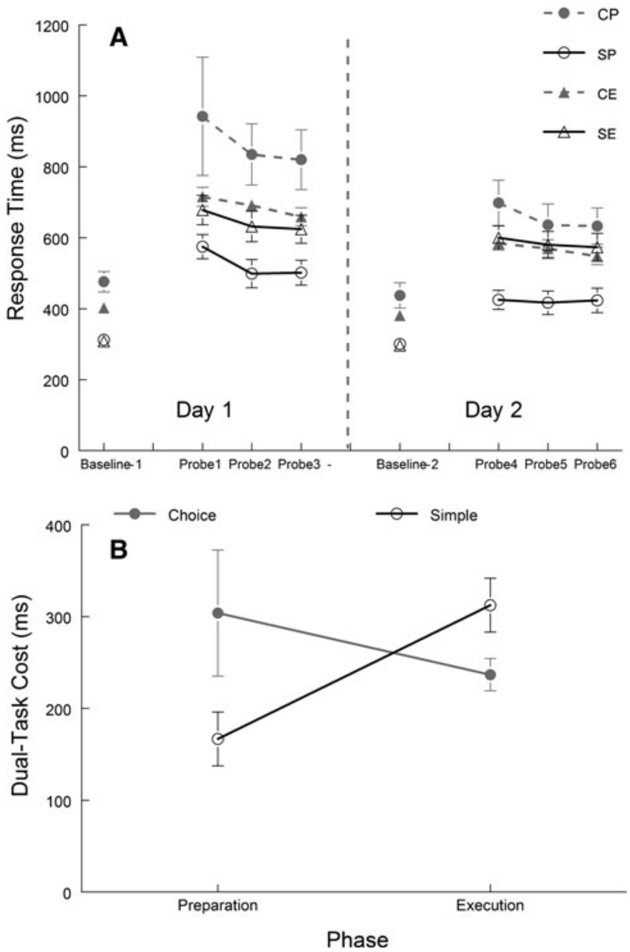

Fig. 4 **a** Participants' response time (ms, mean ± SEM) to the audio stimulus under single-task conditions (*Baseline 1* and *2*) and dual-task conditions (*Probe 1–6*) during practice on Day 1 and 2. The Choice-Preparation (*CP*) and Choice-Execution (*CE*) groups had longer response times than the Simple-Preparation (*SP*) and Simple-Execution (*SE*) groups under single-task condition (*Baseline 1* and *2*). The SP group had shorter response times than the CP group under dual-task conditions (*Probe 1–6*), but the SE group showed similar response times as the CE group. **b** Dual-task cost (ms, mean ± SEM) is the difference between response times measured under dual-task conditions (*Probe 1–6* in **a**) and single-task conditions (*Baseline 1* and *2* in **a**). Dual-task cost was collapsed across practice blocks. The CP group had slightly higher cost than the SP group, while the SE group had significantly higher cost than the CE group

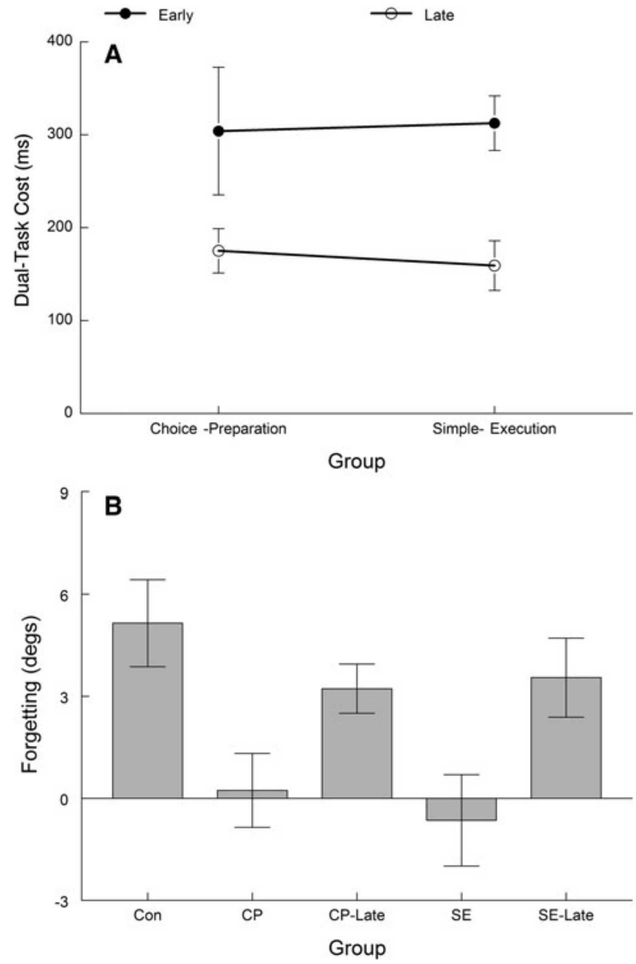

Fig. 5 **a** Dual-task cost (ms, mean ± SEM) for the two late groups (*CP-Late* and *SE-Late*) and the two early groups (*CP* and *SE*). The late groups demonstrated lower dual-task cost than the early groups. **b** Forgetting (degrees, mean ± SEM) measured across the delayed and immediate retention tests. The Choice-Preparation-Late (*CP-Late*) and Simple-Execution-Late (*SE-Late*) groups did not show evidence for enhanced learning confirmed by comparable forgetting as the Control-NoProbe group (*Con*) and greater forgetting than the Choice-Preparation (*CP*) and Simple-Execution (*SE*) groups

mean age, 28 ± 6 years). On the probe trials, the Choice-Preparation-Late group was probed using the two-choice RT task 500 ms after the "Ready" signal in contrast to the original earlier 50 ms; the Simple-Execution-Late group was probed using the simple RT task 700 ms after movement onset as opposed to the original earlier 300 ms. Studies have shown that dual-task costs measured at the late phases of discrete movements were low (Olivier et al. 2003; Salmoni et al. 1976). Thus, we predicted that this manipulation of probe latency would reduce dual-task cost and subsequently attenuate the enhanced motor learning effect. As predicted, both late probe groups showed a significantly lower dual-task cost compared to the two early probe groups (Choice-Preparation and Simple-Execution) (Fig. 5a, Timing effect: $F_{(1,38)} = 12.21$, $p = .001$). These two late probe groups also did not show any evidence for enhanced learning as evidenced by comparable forgetting as the Control-NoProbe group (Fig. 5b) (Choice-Preparation-Late vs. Control-NoProbe, $p = .24$; Simple-Execution-Late vs. Control-NoProbe, $p = .33$). The post hoc direct comparison of forgetting for the two Choice-Preparation groups did not reach significance (Choice-Preparation-Late vs. Choice-Preparation: $p = .07$). In contrast, the comparison of Forgetting for the Simple-Execution groups was significant (Simple-Execution-Late vs. Simple-Execution: $p = .01$). Therefore, the beneficial effect of dual-task practice on learning was not observed when an equally difficult secondary task was presented later in either of the movement phases when concurrent engagement of similar processes would not be expected.

Discussion

Our novel design that used two levels of secondary task difficulty and primary task phase provides compelling evidence that it is the concurrent engagement of similar processes, and not the difficulty in the secondary task that mediates the beneficial effects of dual-task practice on motor skill learning. The choice RT task enhanced learning only when it was presented during the preparation but not execution phase. We also found that the simple RT task enhanced learning only when it was presented during the execution but not the preparation phase of the motor task. Further, this double-dissociation seemed to be at least partially associated with the dual-task cost measured during practice. The choice RT task presented during preparation and the simple RT task presented during execution tended to result in higher dual-task cost during practice than the other two experimental groups (Choice-Execution and Simple-Preparation). Delaying the choice and simple RT tasks during movement preparation and execution, respectively, decreased the dual-task cost and attenuated the enhanced learning effect. Thus, our study resulted in two important findings. First, dual-task interference is not simply determined by the difficulty or amount of information embedded in the secondary task. Instead, it is more likely that the similarity of the processes between the two tasks determines the level of interference. Second, the enhanced motor learning effect of dual-task practice is most likely supported by the similarity hypothesis and not the difficulty hypothesis.

Dual-task cost during practice

The dual-task cost data measured during practice suggest that dual-task interference might be mediated by the similarity of engaged processes rather than secondary task difficulty. The Choice-Preparation group showed slightly greater dual-task cost than the Simple-Preparation group during practice. The difference was not statistically significant partly due to high between-subject variability in the Choice-Preparation group. One could interpret this finding simply based on the processing demand of the choice RT task. On the other hand, we could also interpret this finding from the concurrent engagement of planning processes perspective. Assuming that the primary task engages response planning processes during the preparation phase, the choice RT task, compared to the simple RT task, is more likely to engage similar processes as the primary task. This concurrent engagement of response planning processes may lead to high levels of interference as there is a significant degree of attentional resource sharing between the primary and choice RT tasks, based on Wicken's multiple resource model. We also observed that the simple RT task presented during movement execution led to a higher level of interference during practice than the choice RT task. Thus, it does not seem like the difficulty level of the RT task is the factor mediating this rather surprising observation. We suggest that this is because the simple RT task and primary task execution engage similar motor response execution processes and tax the same resource pool. On the other hand, the choice RT task presented during execution phase may not simultaneously engage similar motoric processes as the primary task. By the time when the choice RT task engaged the motoric processes during arm movement execution, the primary task may no longer engage the same motoric processes as the movement is close to the end. Hence, little dual-task interference would be expected. The lower dual-task cost during practice found in the Choice-Execution group supports this argument. This argument is further supported by the control experiment in which the simple RT task is presented later during movement (Simple-Execution-Late group). When the motoric processes of the simple RT task are evoked at a time when the primary task is no longer engaging similar processes, there was little interference (Fig. 5a).

Taken together, assuming that the working mechanisms for the dual-task interference observed during movement preparation and execution phases are similar, our results provide evidence in support of a unique pattern of process-specific dual-task interference. The level of interference during dual-task performance is likely mediated by engaging similar processes rather than by the difficulty in the secondary task.

Dual-task practice enhances learning

Most importantly, we demonstrated that certain dual-task practice conditions, though interfering during practice, enhanced motor learning. We found that a difficult secondary task (i.e., choice RT task) only enhanced motor learning when it was presented during the movement preparation phase. In contrast, the easy secondary task (i.e., simple RT task) was beneficial when it was presented during the movement execution phase. Thus, it does not seem like the dual-task practice benefit is mediated by task difficulty. One could argue that maybe the choice RT task presented during the execution phase was too challenging and thus did not enhance learning. In other words, there may be an optimal level of secondary task difficulty that is beneficial for learning (Guadagnoli and Lee 2004). If the choice RT task presented during the execution phase imposed too much of a demand on the learners, one would expect to observe a compromised task performance during practice. However, we did not observe such an effect. The Choice-Execution group demonstrated similar primary task performance as the other groups, and even better secondary task performance than the Simple-Execution group. Thus, our results do not support the task difficulty hypothesis suggested by Roche et al. (2007).

Our results differed from Roche et al. (2007) possibly due to two reasons. First, the primary task employed in Roche et al.'s study was a perceptual task in which learners needed to discriminate the orientation of a presented visual stimuli and made appropriate motor responses (left or right click of a computer mouse). Our motor task required learners to transform displayed trajectory information (spatial and temporal) into a complex arm movement. Therefore, it may be that secondary task difficulty modulates dual-task practice benefit for a limited scope of tasks. Second, Roche et al. manipulated secondary task difficulty within similar processing demands of the primary task. For instance, they presented a motoric secondary task (finger tapping with left hand) when participants were executing the primary task response (mouse clicking with right hand) and varied the finger tapping speed (fast vs. slow, fast tapping was considered difficult). Similarly, they presented a perceptual secondary task (flash) either synchronous (easy) or asynchronous (difficult) with the presentation of primary task stimulus. In both cases, they found the difficult secondary tasks led to better primary task learning compared to easy secondary tasks. Therefore, one could argue that Roche et al.'s secondary tasks were both difficult and engaged similar processes as the primary task. The authors did not present the same difficult secondary task at different primary task phases, for example, fast finger tapping during primary stimuli presentation. Thus, their results could potentially be explained by engagement of similar processes as well.

In contrast to the task difficulty hypothesis, our results are more in line with the hypothesis of concurrent engagement of similar processes proposed by Hemond et al. We found that when two tasks engaged similar processes at the same time during practice, as indicated by a high level of dual-task interference, there was enhanced learning during retention. We replicated and extended Hemond et al.'s findings by showing a facilitative effect in a discrete arm task that engages different processes than a sequential finger task. In contrast to Hemond et al., we did not observe the benefits at the end of practice (immediate retention), but rather in delayed retention. In fact, at the immediate retention, the two enhanced groups (Choice-Preparation and Simple-Execution) showed slightly greater movement error. However, these groups showed superior performance at the delayed retention test (Fig. 2a). Post-practice delayed performance is generally deemed as a more stable indicator of learning compared to practice performance (Schmidt and Lee 2005). Our findings are consistent with a well-known motor learning phenomenon, the learning-performance distinction (Kantak and Winstein 2012). It is commonly found in young healthy adults that challenging practice conditions hinder performance during practice but facilitate post-practice delayed performance. Thus, while Hemond et al. provided evidence that concurrent engagement of similar processes enhances motor performance, we provide evidence for enhanced *motor learning*. To our best knowledge, this study is the first one to demonstrate the beneficial effects of concurrent engagement of similar processes on motor learning.

What are the possible mechanisms by which concurrent engagement of similar processes enhanced motor learning? Following Hemond et al.'s (2010) explanation, we hypothesize that specific types of secondary task may facilitate engagement of important neural circuitry that is associated with learning of the primary task. Modulating the important circuitry may be easier when it is already pre-activated (Lang et al. 2004). Several studies have described increased activation of common neural network shared by the two tasks during dual-task performance (Adcock et al. 2000; Klingberg 1998; Klingberg and Roland 1997; Remy et al. 2010; Van Impe et al. 2011). It is argued that dual-task interference may arise from the competition of the shared neural resource as suggested by the increased activation in overlapped areas (Klingberg 1998). This argument is in line with our explanations for the interference pattern observed in our study. It is possible that the choice RT task presented during preparation and the simple RT task during execution facilitate the engagement of premotor and motor cortices, respectively. Premotor (Boyd and Linsdell 2009) and motor (Lin et al. 2011) areas have been shown to be associated with enhanced motor learning. Hence, it may be that concurrent engagement of similar processes during practice facilitates the engagement of these specific neural substrates that subsequently enhances learning. Future carefully designed and hypothesis-driven studies are needed to examine the neural mechanisms implementing the dual-task practice benefits on motor learning.

There are a few limitations of this study, including the relatively small sample sizes. Our explanations assume that the processes in the RT tasks are engaged in serial order. We have no direct measurement of the specific processes engaged; thus, our conclusion regarding concurrent engagement of similar processes is built solely upon indirect evidence. We also assume that the working mechanisms of the dual-task interference during the movement preparation and execution phases are similar. This assumption needs further direct testing. We used only one temporal specification for our experimental controls (the late groups) while one could also manipulate the nature of the processes engaged (e.g., a three-choice RT task, primary task practice schedule, etc.) to further examine this phenomenon. Finally, the connection we make between our results and neuroimaging evidence is at most speculative. We urge future studies to address these limitations.

In conclusion, a distracting secondary task, if engaging similar processes as the primary task, can enhance primary task learning even with a relatively low probe frequency. It does not seem that the level of secondary task difficulty modulates human dual-task performance; rather, our findings strongly suggest that the common processes engaged by both tasks are the essential elements. Concurrent engagement of similar processes benefits *motor learning* after practice, even though it creates a high level of interference during practice.

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