

# Paradoxical Benefits of Dual-Task Contexts for Visuomotor Memory

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## Abstract

It is generally thought that increased attention helps when one is learning a new task. However, using a dual-task paradigm, we showed that the rate of visuomotor learning was the same regardless of attentional distraction caused by a secondary task. Yet, when participants were tested later, a motor skill learned under distraction was remembered only when a similar distraction was present; when participants were tested without the distracting task, their performance reverted to untrained levels. This paradoxical result, in which the level of performance decreases when more attentional resources are available, suggests that the dual-task context, or the lack thereof, acts as a vital context for learning. This task-context-dependent “savings” was evident even when the specific secondary task or sensory modality differed between learning and recall; thus, the dual tasking, rather than the specific stimuli, provides context. This discovery suggests that the success of learning and rehabilitation programs may be diminished if they are developed without consideration of the role of task contexts.

## Keywords

attention, motor processes, memory, learning, task context

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In many daily activities, visuomotor skills are used in a complex environment in which multiple stimuli compete for limited attentional resources. For instance, while driving, people must divide their limited attentional resources between maneuvering the car and many other tasks, such as looking in the mirror, using turn signals, and avoiding pedestrians. Because attention has been viewed as a necessary resource that facilitates many cognitive functions, including learning, it is not surprising that dividing attentional resources across tasks can be very costly for performance (for a review, see Pashler, 1998). In accord with this notion, previous studies have shown that performing a concurrent task can interfere with sequence learning (Curran & Keele, 1993; Nissen & Bullemer, 1987) and sensorimotor adaptation (Taylor & Thoroughman, 2007, 2008). Thus, one might expect that minimizing attentional distraction during visuomotor learning would always be beneficial. However, these previous studies have focused exclusively on immediate detrimental effects on motor performance, leaving unaddressed the question of how divided attention affects memory formation or retrieval.

Furthermore, the level of attentional distraction can often change between when a motor skill is learned and when it is subsequently recalled; how this change might affect recall is unknown. For instance, a person who has had a stroke might regain movement control while in a quiet rehabilitation setting but will ultimately be required to use the recovered skill in an everyday situation with many distractions. Likewise, a student may learn how to play the violin in a lively classroom and later have to perform in a quiet hall for a recital. Are motor skills learned free of distraction diminished at recall when distractions are present? Conversely, are motor skills learned when distractions are present diminished at recall when there are no distractions?

In prior work on episodic memory, researchers found improved recall of specific episodes or information when encoding and retrieval took place in the same

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environmental context. For example, a pioneering study showed that when divers learned word lists while diving, they recalled the lists best when underwater; in contrast, words learned on land were best recalled on land (Godden & Baddeley, 1975). Likewise, professional sports teams often show a home advantage, perhaps because motor skills are best retrieved at the home stadium, where the environmental contexts of practice and performance are consistent (Courneya & Carron, 1992). Although the benefits of having learning and recall take place in consistent environmental contexts are well documented, it is not known whether fully allocating attention to motor learning or performing a secondary distractor task can also form a task context that has to be reinstated at recall for successful retrieval of visuomotor memory.

In the current study, we used a recently developed dual-task paradigm (Bédard & Song, 2013; Song & Bédard, 2013) that pairs a visuomotor adaptation task with an attention-demanding discrimination task to examine how consistency in the availability of attentional resources across learning and recall affects different stages of visuomotor learning, including motor error reduction, memory formation, and recall. This study extends a recent observation that performing a secondary task during visuomotor rotational adaptation to one direction limits the range and magnitude of generalization to untrained directions without impairing the rate of adaptation during training (Bédard & Song, 2013).

Two questions that remained unclear were how various attentional demands of a secondary task modulate immediate motor performance and how consistency in task context between learning and recall affects memory formation and retrieval. Thus, in Experiment 1, to examine whether attentional resources are critical for adaptation, we parametrically varied the attentional demands (none, low, and high) of a secondary rapid serial visual presentation (RSVP) task during visuomotor learning. We then evaluated the effect of consistency of task contexts (i.e., single vs. dual) to determine whether memory of the newly acquired visuomotor skill depended on consistent performance of a single task or of a dual task during both learning and recall. We were surprised to find that when participants learned the motor skill in a dual-task environment, they showed evidence of learning during the recall phase only when the secondary task was again included; removing the secondary task at recall resulted in no evidence of learning. In Experiment 2, we then examined whether this task-context-dependent memory transferred beyond the specific task environment in which it was initially formed. Does the secondary task have to be the same during learning and recall for the skill to be maintained, or does simply dividing attention between two tasks provide sufficient task context? Our

results support the latter notion: The requirement to perform two tasks, regardless of whether the secondary task is the same during learning and recall, provides sufficient task context to facilitate motor recall.

## Experiment 1: Consistent Dual-Task Demands Enhance Memory Retrieval

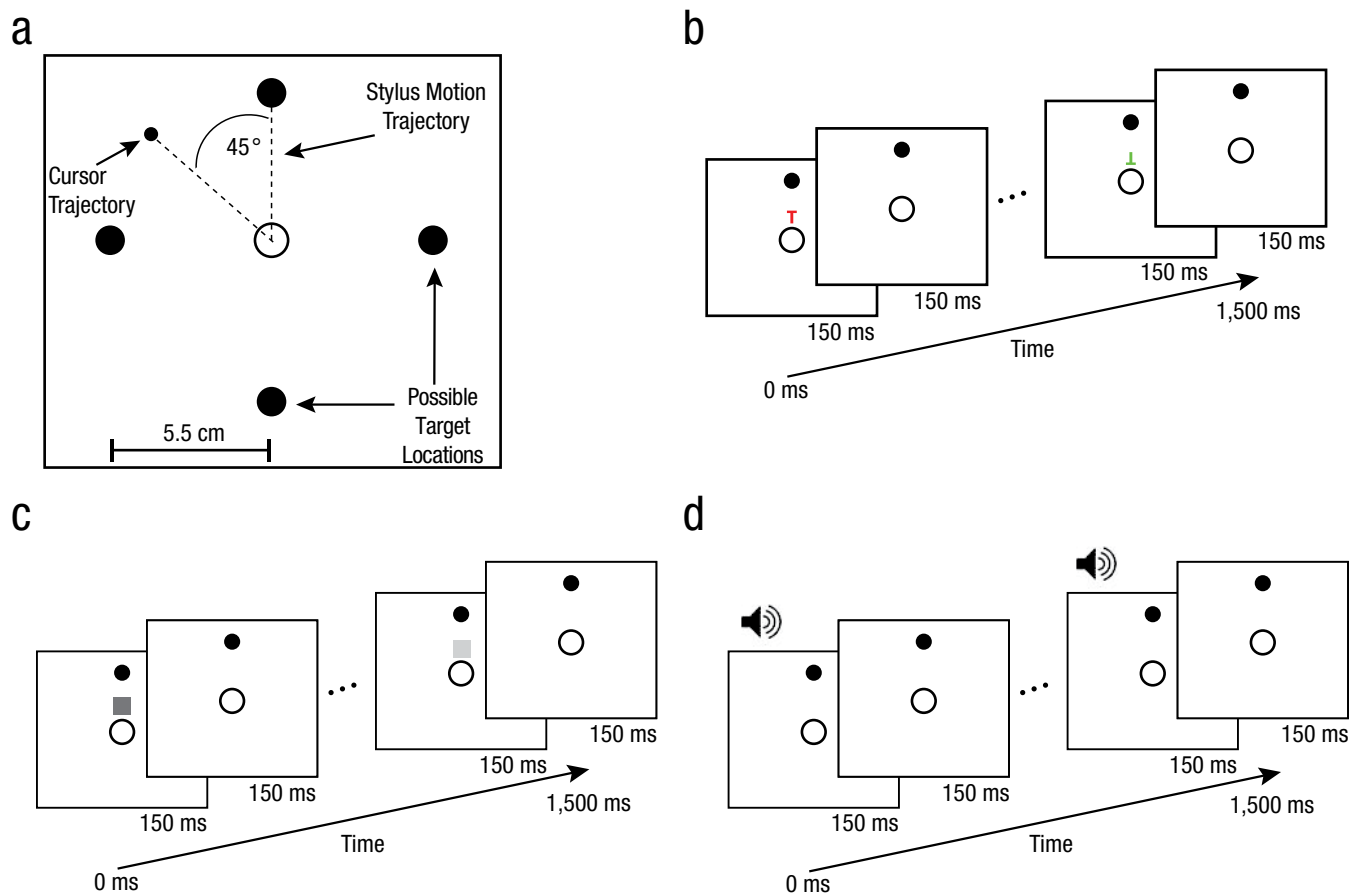
### Method

**Participants.** A total of 48 right-handed participants (age range = 19–23 years) with normal color vision and normal or corrected-to-normal visual acuity participated in this experiment. The number of participants per group ( $n \geq 9$ ) was determined on the basis of our prior studies, which used a similar dual-task paradigm and experimental design (Bédard & Song, 2013; Song & Bédard, 2013) and obtained reliable effect sizes ( $\eta_p^2 > .26$ ).<sup>1</sup> The sample size is also in accord with the typical range used in other visuomotor adaptation studies (e.g., Krakauer, Pine, Ghilardi, & Ghez, 2000; Taylor & Thoroughman, 2007, 2008; Wu & Smith, 2013). The experimental protocol was approved by the institutional review board at Brown University. Participants received monetary compensation or course credit.

**Apparatus.** In a dimly illuminated room, participants sat in a chair about 57 cm away from an Apple iMac computer with a 21-in. screen (refresh rate = 60 Hz). They held a stylus in the right hand to perform a goal-directed reaching task. The tip of the stylus rested on a touch screen (Magic Touch; Keytec, Garland, TX) that lay flat on a table and aligned with each participant's midline and the center of the monitor. We presented visual stimuli on the monitor and recorded cursor displacement using MATLAB (Version R2008b; MathWorks Inc., Natick MA) and functions from PsychToolbox (Version 3; Brainard, 1997; Pelli, 1997). Moving the stylus moved a cursor (diameter: 0.5 cm) on the monitor.

### Tasks

**Visuomotor adaptation task.** In the primary task, participants had to move the cursor from a starting base (annulus with a diameter of  $1^\circ$ , corresponding to 1 cm) in the center of the screen toward visible reach targets ( $1^\circ$  diameter) located 5.5 cm away at 3, 6, 9, and 12 o'clock in relation to the starting base. The visual stimuli were white on a black background. In each block of four trials, the target appeared once in each of the four locations, in random order. The target remained visible for the entire trial (1,500 ms). There were two types of trials. In null trials, the cursor followed stylus motion normally; in rotation trials, the cursor direction was rotated  $45^\circ$  counterclockwise to force movement adaptation (Fig. 1a).



**Fig. 1.** Task schematics for Experiments 1 and 2. In the illustration of the reaching task (a), the filled circles indicate possible target locations, and the open circle indicates the starting base. Reach targets appeared one at a time and remained visible for the entire trial (1,500 ms). In null trials, the cursor followed stylus motion normally, whereas in rotation trials, the cursor direction was rotated by 45° counter-clockwise from the reach trajectory. The dashed lines show the trajectory of the stylus and of the cursor on rotation trials. In Experiment 1, the rapid serial visual presentation (RSVP) task (b) was the only secondary task. In Experiment 2, the secondary task was always the RSVP task during the adaptation phase but varied during the recall phase; in some groups, it was the RSVP task, and in others, it was (c) a brightness discrimination task or (d) a sound discrimination task. In each trial, the visual or auditory stimuli for the secondary task were presented sequentially for 150 ms, with 150-ms gaps between stimuli (total of 1,500 ms). In the RSVP task, five upright or inverted *T*s of various colors were presented. In the brightness discrimination task, five gray 1-cm<sup>2</sup> squares of low, medium, or high luminance were presented. In the sound discrimination task, five tones of low, medium, or high frequency were presented. For all the secondary tasks, participants had to report at the end of each trial how many relevant targets (one, two, or three) were presented in that trial.

After 40 practice null trials with no cursor perturbation, each participant performed four sequential experimental phases: baseline (40 null trials), adaptation (160 rotation trials), de-adaptation (80 null trials), and recall (80 rotation trials).

**Secondary RSVP task.** On every trial, five *T*s (0.5 × 1 cm) randomly selected from two orientations (upright or inverted) and five colors (red, white, green, purple, or orange) appeared sequentially 0.5 cm above the starting base (Fig. 1b). One *T* was presented every 300 ms and remained visible for only 150 ms (for a total duration of 1,500 ms). Attentional load for the RSVP task was manipulated between participants (Table 1). Participants in the no-load condition were instructed to ignore the *T*s and

were never probed about their occurrence. Participants in the low- and high-load conditions were instructed to count the number of target *T*s. In the low-load condition, there was a single target, defined by a single feature, color (e.g., a green *T*). In the high-load condition, there were two targets, defined by a conjunction of features, color and orientation (e.g., an upright red *T* and an inverted green *T*). The number of target *T*s in each trial varied randomly among one, two, and three with equal probability. Thus, the probability of each number of targets was 33%. At the end of each trial, participants in the low- and high-load conditions reported the number of targets observed (one, two, or three) by pressing a key on a computer keyboard with the left hand. Participants in the no-load condition pressed a key in response to a

**Table 1.** Secondary Tasks Performed by the Groups in Experiments 1 and 2

Group	Experiment	Baseline	Adaptation	Recall
None-none	1 and 2	—	—	—
None-high	1	—	—	High-load RSVP
Low-none	1	Low-load RSVP	Low-load RSVP	—
High-none	1 and 2	High-load RSVP	High-load RSVP	—
High-high	1 and 2	High-load RSVP	High-load RSVP	High-load RSVP
High-brightness	2	High-load RSVP/brightness discrimination	High-load RSVP	Brightness discrimination
High-sound	2	High-load RSVP/sound discrimination	High-load RSVP	Sound discrimination

Note: No secondary tasks were performed during the de-adaptation phase between the adaptation and recall phases. RSVP = rapid serial visual presentation.

visual cue at the end of each trial (e.g., “Press button 1”). *T*s appeared on every trial of all experimental phases, so the visual stimuli were the same across all participants.

**Procedure.** All participants performed the visuomotor adaptation task (Fig. 1a), but the RSVP task (Fig. 1b) was performed or not depending on group assignment and experimental phase, as indicated in Table 1. To examine how the attentional load of the RSVP task (no, low, or high load) would affect learning and whether the consistency of task state (i.e., whether a participant had to perform two tasks or one) from adaptation to recall would affect recall, we randomly assigned participants to one of five groups, labeled according to the attentional load of the RSVP tasks during the adaptation and recall phases: no load during adaptation phase and no load during recall phase (none-none;  $n = 9$ ), low load during the adaptation phase and no load during the recall phase (low-none;  $n = 9$ ), high load during the adaptation phase and no load during the recall phase (high-none;  $n = 9$ ), high load during the adaptation phase and high load during the recall phase (high-high;  $n = 9$ ), and no load during the adaptation phase and high load during the recall phase (none-high;  $n = 12$ ). Results from the none-high group were less diagnostic than those from the other groups, so we have focused our discussion on the those groups (see Results).

**Data analysis and statistics.** Data-analysis procedures generally followed those used in our previous studies (Bédard & Song, 2013; Song & Bédard, 2013). For the visuomotor task, we filtered the  $x$ - and  $y$ -coordinates of stylus displacements (relative to the target’s actual location) with a low-pass Butterworth filter using a 10-Hz cutoff and then calculated the cursor’s trajectory by taking the square root of the sum of squared  $x$ - and  $y$ -coordinates at each time point. We differentiated the position of the

cursor to obtain tangential velocity; movement was considered to begin when the cursor’s movement exceeded 5% of peak velocity and to end when the cursor’s movement fell below 5% of peak velocity. We measured reaction time as the time elapsed from the onset of the target to the onset of movement and movement time as the time elapsed between the beginning and end of movement. We measured reach error by calculating the angle between the line that joined the starting base to the target and the line that joined the position of the cursor at movement onset to the position of the cursor at peak velocity. Clockwise errors were deemed positive, and counterclockwise errors negative. We averaged reaction time, movement time, and reach error across each block of four trials.

We measured savings, a metric of memory formation, by calculating the average reach error in Blocks 3 to 7 for the adaptation and recall phases and then taking the difference between these averages for the two phases, as in similar work (Krakauer, Ghez, & Ghilardi, 2005). We did not use the data from the first few blocks in the adaptation and recall phases because the high-none and high-high groups had more errors during these blocks than did the none-none and low-none groups, probably because of the initial difficulty of performing the high-load RSVP task and the reaching task simultaneously. Using the data from the first few blocks would have artificially and inappropriately amplified the savings of the none-none and low-none groups.

We used the R software (Version 3.1.0; R Development Core Team, 2014) and MATLAB for data-analysis and statistical analysis. We analyzed the data using mixed-effects analyses of variance (ANOVAs). In these analyses, group was a between-subjects factor, and block and phase were repeated measures. When multiple post hoc comparisons were made, Newman-Keuls correction,  $p < .05$ , was applied. We also calculated effect sizes ( $\eta_p^2$ ).

## Results

**Effect of performing a secondary task during adaptation.** To evaluate how attentional diversion to the RSVP task during adaptation affected both adaptation and subsequent recall, we first compared performance across the none-none, low-none, and high-none groups. First, we confirmed that our secondary-task manipulations were effective. As expected, the low-none group performed the RSVP task better than the high-none group during the adaptation phase (see Fig. S1A legend in the Supplemental Material available online for statistical analysis). Thus, the conjunction RSVP task (high-none group) was indeed harder and required more attentional resources than the single-feature RSVP task (low-none group). There was no difference in RSVP accuracy between the baseline and adaptation phases, which suggests that visuomotor rotational adaptation does not cause additional interference in visual detection (Khan, Song, & McPeck, 2011).

Despite having different levels of attentional load, all three groups reduced reach errors and achieved similar levels of performance by the end of the adaptation phase. This is reflected in their reaching trajectories (Fig. S1B in the Supplemental Material). Furthermore, this equivalent adaptation can be seen directly in the fully superimposed error curves shown in Figure 2a. A two-way ANOVA with group (none-none, low-none, and high-none) and block (all 40 blocks) as factors confirmed this observation. There was no significant main effect of group,  $F(2, 24) = 0.62, p = .55, \eta_p^2 = .05$ , but there was an expected significant main effect of block,  $F(39, 936) = 23.9, p < .0001, \eta_p^2 = .5$ , indicating visuomotor adaptation. We observed a significant interaction,  $F(78, 936) = 1.70, p = .0003, \eta_p^2 = .12$ , which was driven by the higher reach error in the first block among the high-none group than among the none-none and low-none groups, who did not differ from each other. This result suggests that performing the secondary task does not always disrupt the process of decreasing reach error.

However, the level of attentional diversion to the secondary task during the adaptation phase greatly affected savings during subsequent recall,  $F(2, 24) = 4.93, p = .02, \eta_p^2 = .29$  (compare reach error during adaptation and recall in the shaded areas of Figs. 2b–2d). No savings would indicate that a participant's performance reverted to untrained levels during recall, as if the task had never been practiced. As summarized in Figure 2f, the none-none group showed significantly higher savings than the low-none and high-none groups, who did not differ from each other.

Therefore, performing the RSVP task concurrently with the visuomotor adaptation task did not impair immediate motor performance (Fig. 2a). With a parametric manipulation of attentional loads, we replicated and extended what

we observed in our prior work (Bédard & Song, 2013), in which only the none and high-load conditions were compared during visuomotor adaptation. The poor recall performance (lack of savings) in the low-none and high-none groups may suggest that performing the secondary task during adaptation impaired memory formation. However, the inconsistency of task contexts (single task vs. dual tasks) between the adaptation and recall phases could have disrupted memory retrieval in these groups. We therefore assessed whether disruption in memory formation or failure in memory retrieval best explained the data.

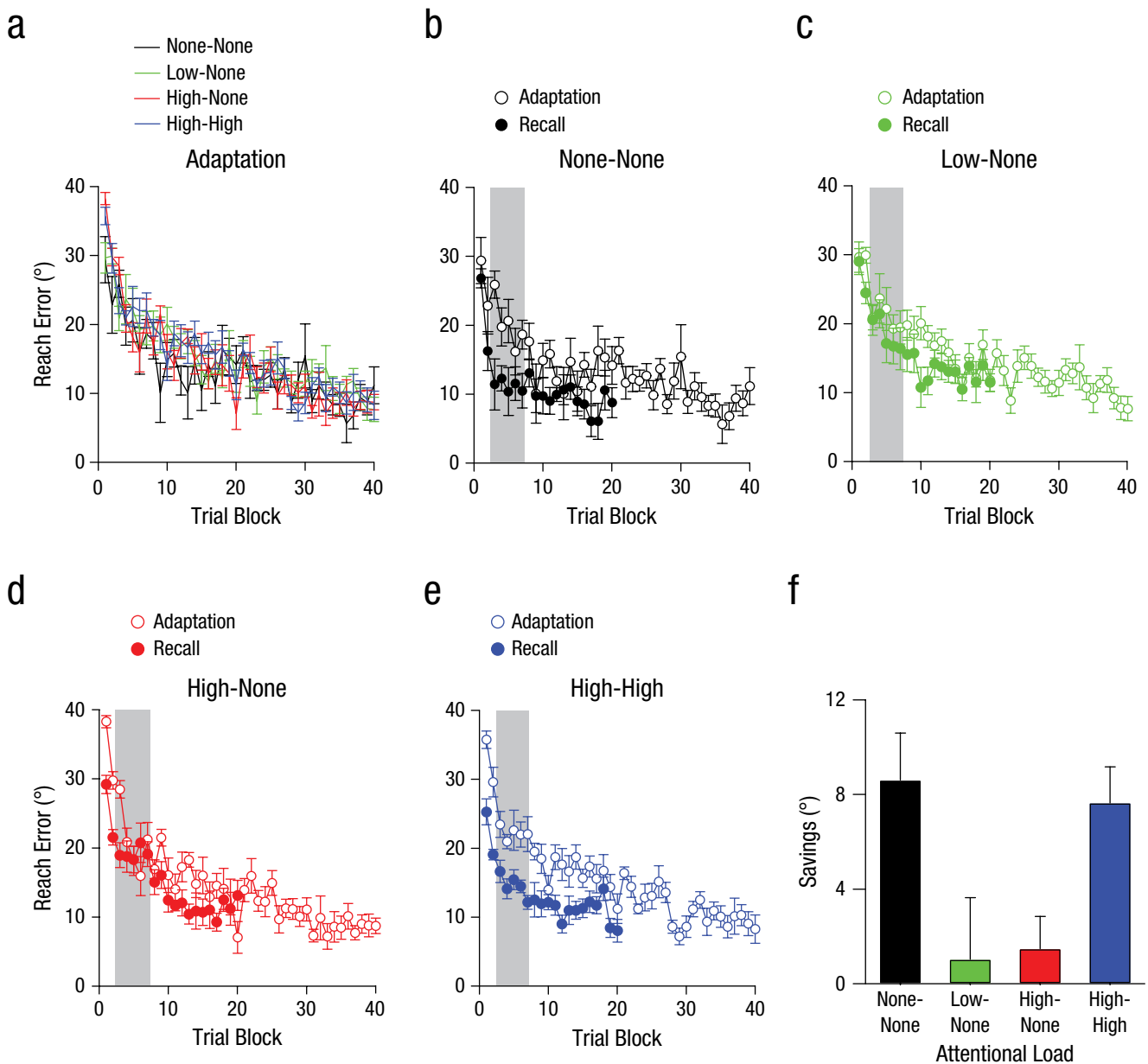
### **Effect of consistency in task context between learning and recall.**

To evaluate these two alternative possibilities, we compared the performance of the high-high group (consistent dual-task context), who performed the RSVP task during both the adaptation and the recall phases, with the performance of the none-none (consistent single-task context) and high-none (inconsistent task context) groups. We found that the visuomotor adaptation task did not interfere with the high-high group's performance of the RSVP task in the baseline, adaptation, and recall phases and that their RSVP performance was similar to that of the high-none group (see Fig. S1A in the Supplemental Material for statistical analysis).

During adaptation, the high-high group showed a reduction in reach error similar to that of the none-none and high-none groups (Fig. 2a). This was confirmed by a two-way ANOVA with group (none-none, high-none, and high-high) and block (all 40 blocks) as factors. There was no main effect of group,  $F(2, 24) = 0.89, p = .42, \eta_p^2 = .07$ , but there was an expected significant main effect of block,  $F(39, 936) = 32.4, p < .0001, \eta_p^2 = .57$ . A significant interaction,  $F(78, 936) = 1.69, p = .0003, \eta_p^2 = .12$ , was driven by a few blocks (Blocks 11, 13, and 19) in which the groups differed, but without consistent patterns.

The critical comparison concerns the savings (Fig. 2f) of the high-high group (Fig. 2e) compared with those of the none-none (Fig. 2b) and high-none groups (Fig. 2d). If divided attention disrupted memory formation, there should have been little or no savings in the high-high group, much as in the high-none group. However, if the inconsistency of task contexts between learning and recall caused interference with memory retrieval in the high-none group, the savings of the high-high group should have been greater than the savings of the high-none group and similar to that of the none-none group.

Figure 2f clearly shows that the high-high group, who performed the dual tasks throughout both the adaptation and recall phases, had a level of savings similar to that of the none-none group and higher than that of the high-none group,  $F(2, 24) = 6.91, p = .004, \eta_p^2 = .37$ . Thus, the attentional division created by the RSVP task did not weaken participants' underlying memory. Instead, these



**Fig. 2.** Results from Experiment 1. The graph in (a) shows reach error for each group as a function of trial block in the adaptation phase. The graphs in (b), (c), (d), and (e) show reach error in the adaptation and recall phases as a function of trial block separately for the (b) none-none, (c) low-none, (d) high-none, and (e) high-high groups ( $n = 9$  in each group). The gray area in each panel indicates the blocks that were used to calculate savings. In (f), savings are plotted as a function of group. Error bars indicate 1 *SE*.

results indicate that the inconsistency of the task context between adaptation and recall impaired memory retrieval for the high-none group. This suggests that increasing availability of attentional resources at recall can be paradoxically disadvantageous. However, the higher savings in the none-none group show that full attention to motor performance at recall is not by itself disadvantageous.

Results for the none-high group provide converging evidence for task-context-dependent memory retrieval,

as this group also showed no significant savings ( $M = 0.39$ ,  $SE = 2.04$ ),  $t(11) = 0.19$ ,  $p = .85$ . However, this lack of savings could also have been due to the sudden introduction of a secondary task at recall. Thus, this group had weaker analytical value, because this suddenness introduced a complication not present in the other groups. Thus, in our subsequent experiment, we did not include any group in which a secondary task was introduced during recall.

These results clearly demonstrated that a consistent task context (single task vs. dual task) enhanced participants' success in recalling newly acquired visuomotor memories. It is important to note that the relevant factor was task consistency, not low-level consistency of visual stimuli, because the RSVP stream was presented to all groups during all experimental phases, even when RSVP performance was not required. We also ruled out the possibility that a speed-accuracy trade-off caused the apparent dependency of retrieval success on consistency of the task context, because reaction time and movement time were equivalent across all groups (see Figs. S1C and S1D in the Supplemental Material for statistical analysis).

In sum, Experiment 1 demonstrated that although diverting attention to a secondary task during adaptation did not impair memory formation, inconsistent task contexts (single task vs. dual task) during adaptation and recall impaired retrieval of visuomotor memories. In Experiment 2, we examined whether the success of memory retrieval was attributable to simple repetition of the same task between adaptation and recall or to consistency in attentional diversion to a secondary task, regardless of its nature.

## Experiment 2: Consistent Task Contexts, but Not the Same Tasks, Are Required for Memory Retrieval

### Materials and methods

**Participants.** A total of 50 new right-handed participants (age range = 19–23 years) with normal color vision and normal or corrected-to-normal visual acuity participated in this experiment. The experimental protocol was approved by the institutional review board at Brown University. Participants received monetary compensation or course credit.

**Tasks.** The visuomotor adaptation task (Fig. 1a) and the no-load and high-load RSVP tasks (Fig. 1b) used in Experiment 1 were used again. We also used two new secondary tasks: brightness discrimination (Fig. 1c) and sound discrimination (Fig. 1d). The brightness discrimination task was similar to the RSVP task, but instead of  $T_s$ , five gray squares ( $1 \text{ cm}^2$ ) of three different luminance levels (low, medium, high) appeared sequentially 0.5 cm above the starting base (Fig. 1c). Participants were asked to count the number of low- and high-luminance squares presented; the reference medium-luminance square was presented before each trial. The number of relevant luminance squares varied randomly among one, two, and three with equal probability. Thus, the probability of each number of targets was 33%. Participants reported the number of targets observed (one, two, or three) at the

end of each trial by pressing a key on a keyboard with the left hand.

The sound discrimination task was the same as the brightness discrimination task except that five tones of three different frequencies (low, medium, high), rather than five gray squares, were presented sequentially (Fig. 1d). Participants were asked to count the number of low- and high-frequency tones presented. The number of relevant high- and low-frequency tones varied randomly among one, two, and three with equal probability. Thus, the probability of each number of targets was 33%. Participants reported the number of targets observed (one, two, or three) at the end of each trial by pressing a key on a keyboard with the left hand.

**Procedure.** The procedure was similar to that in Experiment 1 except for a few modifications. First, in addition to the none-none, high-none, and high-high groups, we tested groups with new secondary tasks (Table 1): a brightness discrimination task (high-brightness group;  $n = 10$ ) and a sound discrimination task (high-sound group;  $n = 10$ ). Therefore, both of the new groups performed a high-load RSVP task followed by a discrimination task during the baseline phase, a high-load RSVP task during the adaptation phase, and a brightness or sound discrimination task during the recall phase. The important difference was that although these groups also performed a secondary task at recall, that task was very different from the secondary task during adaptation.

Second, although our previous study (Song & Bédard, 2013) showed that eye movements are unlikely to affect visuomotor adaptation, we controlled eye movements in Experiment 2 as a precaution, because it is possible that the effects observed in Experiment 1 resulted from between-group differences in eye movement strategies. We required participants to maintain gaze within a  $1^\circ$ -radius circle around the starting base for the whole duration of each trial. We used an eye tracker (EyeLink II; SR Research, Ottawa, Ontario, Canada) with a 250-Hz tracking rate to monitor gaze position. As soon as gaze was broken, the trial was aborted and repeated immediately, so that all participants performed the same number of trials. Less than 5% of trials were aborted.

**Data analysis and statistics.** Data-analysis procedures were the same as in Experiment 1.

## Results

**Robust task-context-dependent memory retrieval: replication with controlled eye movements.** Results for the high-none and high-high groups (see Figs. S1 and S2 in the Supplemental Material) showed that controlling eye movement did not substantially affect the pattern of

findings for accuracy in the RSVP task. In general, however, the fixation requirement lowered RSVP accuracy, probably because of the added difficulty of performing the task using peripheral vision. We compared the performance of the none-none, high-none and high-high groups in Experiment 2 and replicated the pattern of visuomotor adaptation (Figs. 3a–3c). All three groups had similar decreases in reach errors across the whole adaptation phase. An ANOVA revealed that no significant main effect of group, an expected main effect of block (all 40 blocks), and a significant interaction,  $F(2, 27) = 0.97, p = .39, \eta_p^2 = .07$ ;  $F(39, 1053) = 78.8, p < .0001, \eta_p^2 = .74$ ; and  $F(78, 1053) = 1.77, p < .0001, \eta_p^2 = .11$ , respectively. The interaction was due to a few blocks (Blocks 2 and 7) in which the groups differed but without consistent patterns.

We replicated the results of Experiment 1 in that the none-none and high-high groups had higher savings than the high-none group,  $F(2, 27) = 5.2, p = .01, \eta_p^2 = .28$  (Fig. 3f). Thus, we found that a consistent dual-task context paradoxically enhances recall, even when eye movement is controlled. To further ensure the robustness of task-context-dependent memory retrieval, we replicated our results in a separate within-participants design ( $n = 10$ ), again obtaining converging evidence (see Fig. S3 in the Supplemental Materials for details and statistical analyses).

**Reinstatement of task contexts with different task requirements and sensory modalities.** The primary goal of Experiment 2 was to determine whether the key to successful visuomotor memory retrieval after learning in a dual-task context is to perform the same secondary task during adaptation and recall (e.g., RSVP). If successful retrieval depends on the consistency of task contexts from adaptation to recall, irrespective of the task's requirements or sensory modality, then the high-brightness and high-sound groups, who performed different secondary tasks during adaptation and recall, should have shown savings similar to those of the none-none and high-high groups, who repeated the same secondary task, and greater than those of the high-none group.

Both the high-brightness and high-sound groups (Figs. 3d and 3e) reduced reach error during the adaptation phase, as did the none-none, high-none, and high-high groups (Figs. 3a–3c). A two-way ANOVA revealed no significant main effects of group,  $F(4, 45) = 0.46, p = .77, \eta_p^2 = .04$ , and an expected main effect of block,  $F(39, 1755) = 130.05, p < .0001, \eta_p^2 = .74$ . A significant interaction was driven by a few blocks (1 and 12) for which a consistent pattern was not observed,  $F(156, 1755) = 1.31, p = .008, \eta_p^2 = .10$ .

Figure 3f shows that savings for the high-brightness and high-sound groups were very similar to those for the

none-none and high-high groups, and savings in all these groups were higher than savings in the high-none group,  $F(4, 45) = 2.77, p = .04, \eta_p^2 = .20$ . Thus, the successful savings during recall cannot be attributed to performing the same secondary task or tasks with sensory similarity during learning and recall. Rather, the consistency of the abstract task context (single vs. dual) from adaptation to recall can overcome changes in the secondary task and ensure proper memory recall.

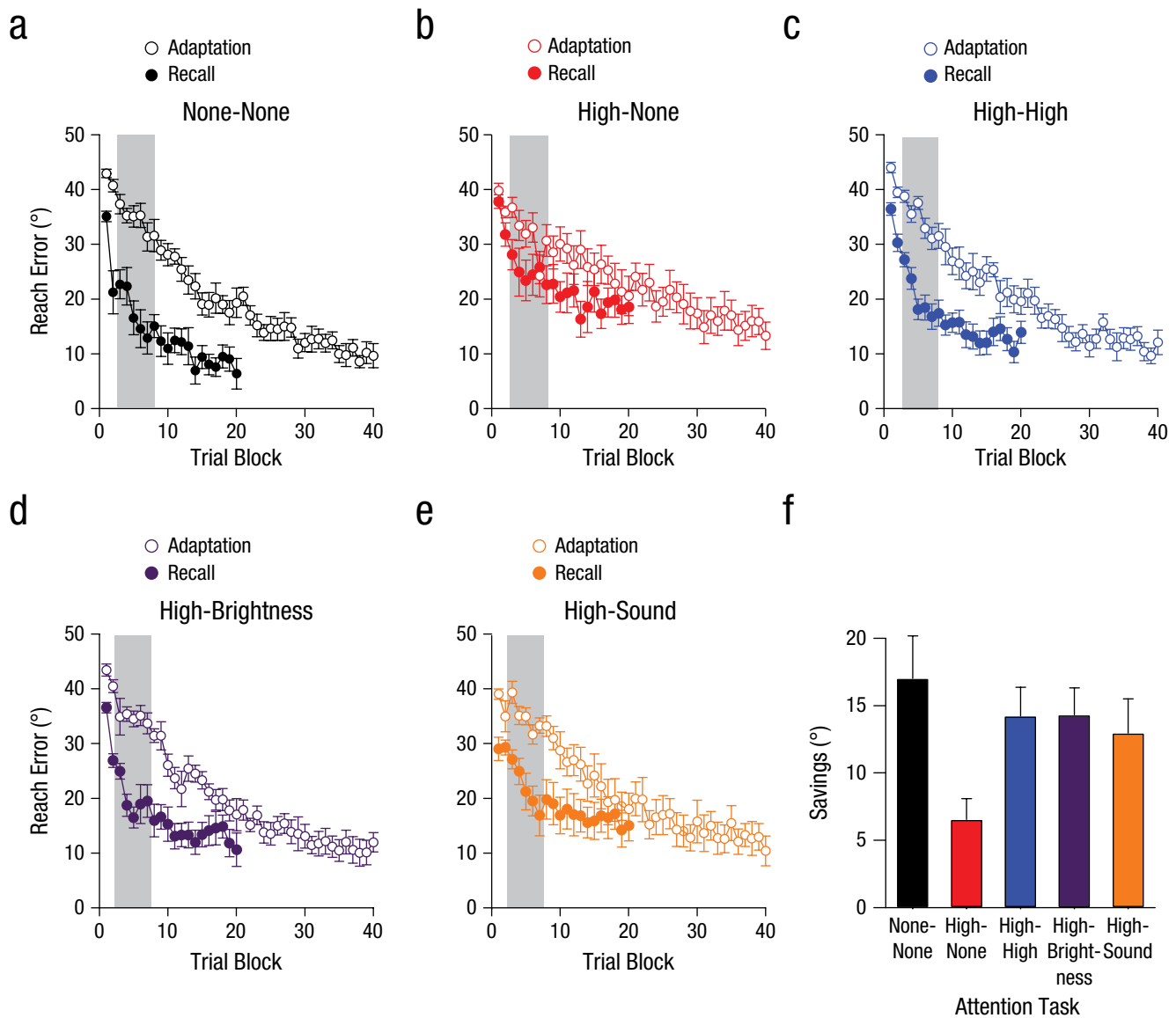
## Discussion

In accord with the well-recognized capacity-limit view of attention, it has been assumed that concurrent performance of a secondary task limits the amount of residual attentional resources available for a primary task (Joseph, Chun, & Nakayama, 1997; Raymond, Shapiro, & Arnell, 1992). However, we observed that as long as attention was consistently divided between two tasks (high-high group) or undivided by a secondary task (none-none group), recall performance was high. Conversely, regardless of the availability of attentional resources at recall, visuomotor memory retrieval failed when the consistency of task contexts was disrupted (high-none and none-high groups). Thus, even under conditions in which it is more difficult to engage in attentional selection of the motor task, repeated task context (i.e., consistently diverting attention to a secondary task) is beneficial for recalling past learning. We suggest that rather than simply acting as a resource for visuomotor learning processes, full attention to motor performance, or the lack thereof, can act as an internal task context for visuomotor memory retrieval.

Our results differ from those of previous studies on episodic memory, in which the divided attention created by a secondary task at encoding significantly reduced subsequent memory performance, whereas divided attention at retrieval affected memory performance only minimally. This asymmetry suggests that attention and episodic memory share resources during encoding but not retrieval (Anderson et al., 2000; Fletcher et al., 1995; Naveh-Benjamin, Guez, & Marom, 2003; Rohrer & Pashler, 2003). We propose that diversion of attention to a secondary task has different effects on episodic memory and visuomotor memory encoding: It interferes with a central resource for episodic memory processes, whereas it is integrated as an internal task-context cue for visuomotor memory formation.

For decades, the success of episodic memory retrieval has been shown to depend on whether the coincidental environmental context at the time of learning is reinstated at recall (Godden & Baddeley, 1975; S. M. Smith & Vela, 2001). On the surface, this reinstatement of environmental context in episodic memory retrieval appears to





**Fig. 3.** Results from Experiment 2. The first five graphs show reach error in the adaptation and recall phases as a function of trial block separately for the (a) none-none, (b) high-none, (c) high-high, (d) high-brightness, and (e) high-sound groups ( $n = 10$  in each group). The gray area in each panel indicates the blocks that were used to calculate savings. In (f), savings are plotted as a function of group. Error bars indicate 1 SE.

operate similarly to the reinstatement of task context in visuomotor memory retrieval, as observed in the present experiments. However, in prior studies on episodic memory (Eich, 1980), consistent external contextual cues took priority over consistent internal states for memory retrieval; by contrast, we repeatedly demonstrated that consistent task contexts can form an internal cue that overrides the same external environmental cue (e.g., RSVP streams). Moreover, we showed that it is not necessary to perform the same secondary task (e.g., RSVP, brightness discrimination, or sound discrimination) or to rely on the same sensory modality in order to reinstate

the task context for motor memory recall. Therefore, task context appears to substantially outweigh environmental context in the effective retrieval of learned motor skills.

In addition to consistent external contexts, consistent internal physiological states induced by alcohol, morphine, cigarettes, scopolamine, or nitric oxide can improve memory recall in both humans and animals (Blasi et al., 2002; DeCarli et al., 1992; Goodwin, Powell, Bremer, Hoine, & Stern, 1969; Nishimura, Shiigi, & Kaneto, 1990; Peters & McGee, 1982). This state-dependent learning relies on the consistency of physiological state at encoding and retrieval. Our results show that performing a single task or

two concurrent tasks can also form an “internal” context without drug-induced physiological changes and can gate the retrieval of visuomotor memory.

How do the surprising findings of our study relate to current understanding of motor learning? According to a representative model of motor learning, two distinct processes operating on different time scales govern motor-error reduction and memory formation: a fast process that learns rapidly from error but has poor retention and a slow process that adapts weakly to error but has strong retention (Joiner, Ajayi, Sing, & Smith, 2011; M. A. Smith, Ghazizadeh, & Shadmehr, 2006). In the present study, we found that the groups did not differ in the adaptation phase, regardless of dual-task context, which indicates equivalent involvement of fast and slow processes was equivalent across all the groups. Yet we still found that memory retrieval was impaired by inconsistent task contexts. Thus, the two-process model, based solely on error-based learning, needs to be updated to account for cognitive effects such as robust task-context modulation of motor learning. This integration will provide a deeper, more principled understanding of training and retention of motor skills.

## Conclusions

The success of learning can be evaluated by assessing whether improvement lasts after training and whether learning in one task generalizes to other tasks. Yet what affects the plasticity of motor learning, or what kind of motor learning paradigm should be applied to promote recovery from motor impairments, is still in question (Andersen, Hwang, & Mulliken, 2010; Kitago & Krakauer, 2013). The present study enhances understanding of how task context (i.e., whether the availability of attentional resources is consistent from motor memory formation to recall) gates the stability of visuomotor learning. We have demonstrated that without consideration of internal task contexts in real-life situations, the success of learning and rehabilitation programs may be undermined. This new discovery of task-context-dependent memory indicates that visuomotor learning processes can be fully understood only by updating current models of attention, motor learning, and memory.

## Author Contributions

J.-H. Song and P. Bédard designed the tasks. J.-H. Song collected the data. J.-H. Song and P. Bédard conducted the data analysis. J.-H. Song and P. Bédard wrote the manuscript.

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## Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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## Supplemental Material

Additional supporting information can be found at <http://pss.sagepub.com/content/by/supplemental-data>

## Note

1. According to Cohen (1988), effect sizes of .02, .13, and .26 are considered small, medium, and large, respectively.

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