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Paradoxical benefits of dual-task contexts for visuomotor memory

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Abstract

It is generally thought that more attention helps when learning a new task. However, using a dual-task paradigm, we showed that the rate of learning was the same regardless of attentional distraction from a secondary task. Yet, when tested later, a motor skill learned under distraction was remembered only when a similar distraction was present. When tested without the distracting task, performance reverted to untrained levels. This paradoxical result, in which 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, it is the dual-tasking, rather than the specific stimuli, that provides context. This new discovery suggests that without considering the role of task contexts, the stability of learning and rehabilitation programs may be diminished.

In many daily activities, visuomotor skills are used in a complex environment where multiple stimuli compete for limited attentional resources. For instance, while driving, we must divide our limited attentional resources between maneuvering the car and many other tasks such as looking in the mirror, using turn signals, and avoiding pedestrians. Since 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 review, see Pashler, 1998). In accord with this notion, previous studies showed that performing a concurrent task can interfere with sequence learning (Curran & Keele, 1993; Nissen & Bullemer, 1987) and sensory-motor 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 the question of how divided attention affects memory formation or retrieval unanswered. Furthermore, the level of attentional distraction can often change between learning of a motor skill and its subsequent recall and how this change may affect later recall is unknown.

For instance, a stroke patient 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. Similarly, 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. What if motor skills learned free of distraction becomes diminished at recall when distractions are present, or vice versa?

Prior work on episodic memory has reported improved recall of specific episodes or information when encoding and retrieval take place in the same environmental context. For example, a pioneering study showed that when divers learned word lists while diving, they recalled the list best when underwater, whereas words learned on land were best recalled on land (Godden and Baddeley, 1975). Similarly, professional sports teams often show a “home advantage,” perhaps because motor skills are best retrieved when environmental contexts between practice and performance are kept consistent at their home stadium (Courneya & Carron, 1992). While the benefits of consistent environmental context in learning and recall are well documented, they do not address whether fully allocating attention to motor learning or the introduction of a secondary distractor task can also form a “task-context” that has to be reinstated at recall for successful visuomotor memory retrieval.

In the current study, we used a recently developed dual-task paradigm (Bédard & Song, 2013; Song & Bédard, 2013) that pairs a visuomotor adaptation task (Fig. 1A) with an attention-demanding discrimination task (Fig. 1B–D) 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 extends on 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; Song & Bédard, 2013). Two questions that remain unclear are 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, we parametrically varied the attentional demands (none, low, and high) of a secondary rapid serial visual presentation task (RSVP; Fig. 1B) during learning to examine whether attentional resources are critical for adaptation. We then evaluated the effect of consistent task contexts (e.g., single vs. dual) to determine if memory of the newly acquired visuomotor skill depended on consistently performing a single or a dual-task during both learning and recall. Surprisingly, performance improved only when the task was constant across learning and recall whereas removing the secondary task at recall resulted in no evidence of learning. In Experiment 2, we then examined whether this task context-dependent memory transfers beyond the specific task environment in which it was initially formed. Does the secondary task during learning and recall have to be the same, or does simply dividing attention between two tasks provide sufficient task context? Interestingly, our results support the latter notion: dual-tasking, not necessarily the task itself, provides sufficient task context to facilitate motor recall.

Experiment 1: Consistent dual-task demands enhance memory retrieval

Materials and Methods

Participants—A total of 48 right-handed participants with normal color vision and normal or corrected-to-normal vision participated in our experiments (19–23 years old). The number of participants per group ($n = 9$) was determined based on our prior studies, which used a similar dual-task paradigm and experimental design (Bédard & Song, 2013; Song & Bédard, 2013), resulting in reliable effect sizes ($\eta^2_p > 0.26$). According to Cohen (1988), effect size measured by partial eta squared of 0.02, 0.13 and 0.26 are considered small, medium and large, respectively. It is also in accord with a typical range used in other visuomotor adaptation studies by various groups (e.g., Krakauer, Pine, Ghilardi, & Ghez, 2000; Taylor & Thoroughman, 2007, 2008; Wu & Smith, 2013). All the experimental protocols were approved by the Institutional Review Board at Brown University. Participants received monetary compensation or a course credit.

Apparatus—In a dimly illuminated room, participants sat on a chair in front of a 21-inch Macintosh iMac computer (refresh rate of 60 Hz) viewed from a distance of ~57 cm and used their right arm to perform a goal-directed reaching task using a stylus pen. We presented visual stimuli on the monitor and recorded cursor displacement using Matlab (R2008b; MathWorks Inc., Natick MA) and functions from PsychToolbox (Brainard, 1997; Pelli, 1997). The stylus pen tip rested on a touch screen (Magic Touch, Keytec) lying on a table, aligned with each participant's mid-line and the center of the monitor. Stylus motion changed the location of a cursor (diameter: 0.5 cm) on the monitor.

Tasks

Visuomotor adaptation task (Fig. 1A): Participants had to reach from a starting base (annulus 1° diameter, corresponding to 1 cm) in the center of the screen towards visible reach targets (1° diameter) located 5.5 cm away at 3, 6, 9, or 12 o'clock. Visual stimuli were white on a black background. Targets appeared once in each of the four locations for each block of four trials. The order of target locations for each block was randomly selected. Reaching occurred in one of two types of trials. In the null trials, the cursor followed stylus motion normally, whereas in the rotation trials, the cursor direction was rotated 45° counterclockwise (CCW) to force movement adaptation. After 40 null practice trials with no perturbation, each participant performed 4 sequential experimental phases: baseline (40 null trials), adaptation (160 rotation trials), de-adaptation (80 null trials), and recall (80 rotation trials).

Secondary RSVP task (Fig. 1B): On every trial, upright or inverted 'T's (0.5 × 1 cm) of various colors (red, white, green, purple or orange) appeared 0.5 cm above the starting base while participants performed the visuomotor adaptation task. In each trial, a total of five 'T's were sequentially presented, one every 300 ms, but each remained visible for only 150 ms (for a total duration of 1500 ms). Attentional loads for the RSVP task were manipulated at three levels across the groups: None, Low, and High (Fig. 1E). In the None group, participants were instructed to always ignore the 'T's and were never probed, whereas in the Low and High groups, targets were defined by a single (e.g., green T) or conjunction feature

(e.g., upright red and inverted green T), respectively. The number of relevant 'T's varied randomly between 1 and 3 with equal probability in the Low and High groups, resulting in a 33 % chance level. Participants reported the number of targets observed (1, 2 or 3) at the end of each trial by pressing a keyboard with their left hand. To equate the extra response and time delay between groups, the None group also pressed a keyboard in response to a visual cue at the end of each trial (i.e., 'Press button 1, 2 or 3'). Importantly, 'T's appeared on every trial of all experimental phases of all groups, so visual stimuli remained the same across all participants.

Procedures—Participants performed the visuomotor adaptation task (Fig. 1A) with or without the RSVP task (Fig. 1B) depending on requirements of the groups and experimental phases as indicated in Fig. 1E. To examine how attentional load of the RSVP task (none, low, high) would affect learning and whether the consistency of dual-task state from adaptation to recall (consistent vs. inconsistent) would affect recall, participants were randomly assigned to one of the five groups: None-None (N=9), Low-None (N=9), High-None (N=9), High-High (N=9), and None-High (N=12). These labels indicate the attentional load of the RSVP task during the adaptation and recall phases as indicated in Fig. 1E.

Data analysis and Statistics—Data analysis procedures mostly followed our previous studies (Bédard & Song, 2013; Song & Bédard, 2013). We filtered the x and y coordinates of stylus displacements with a low-pass Butterworth filter using a 10 Hz cut-off and then calculated the cursor 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 yield tangential velocity and determined the onset and end of movement when the cursor reached 5% of peak velocity. We measured reaction time (RT) as the time elapsed from target appearance to movement onset and movement time (MT) as the time elapsed between movement onset and movement end.

We measured reach error by calculating the angle between the line that joined the starting base to the target with the line that joined the position of the cursor at movement onset to the position of the cursor at peak velocity. Clockwise (CW) errors were deemed positive and CCW errors negative. We averaged RT, MT and reaching error across blocks of four trials (a "cycle").

We measured savings, a metric of memory formation, as the difference between the averages of block 3 to 7 of the adaptation and recall phases as done in similar work (Krakauer, Ghez, & Ghilardi, 2005). We did not use the first few blocks in the adaptation and recall phases as the High-None and High-High groups had higher error during these blocks compared to the None-None and Low-None groups, likely because of the initial difficulty of performing the high-load RSVP task and the reaching task simultaneously. This would have artificially and inappropriately amplified the savings of the None-None and Low-None groups. We used the R Project for Statistical Computing and Matlab for data analysis implementation and statistical analysis.

We used mixed effects ANOVAs with Groups as a between-subjects factor, Blocks and Phases as repeated measures, and participants as a random factor. When multiple post-hoc

comparisons were made, Newman-Keuls correction at $p < 0.05$ was applied. We also calculated the effect sizes using the partial eta squared metric (η^2p).

Results

No disruption of motor performance by dual-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. To begin, 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 (Fig. S1A; see legend for statistical analysis). Thus, the conjunction RSVP detection task (High-None group) was indeed harder and required more attentional resources than the single feature RSVP (Low-None group). Interestingly, there was no RSVP accuracy difference between the baseline and adaptation phases. This result suggests that visuomotor rotational adaptation does not cause additional interference in visual detection (Khan, Song, & McPeck, 2011).

Regarding reaching error during the adaptation phase, despite having differing 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 trajectories (Fig. S1B). Furthermore, this equivalent adaptation can be directly seen in the fully superimposed error curves shown in Fig. 2A. A two-way ANOVA with Groups (None-None, Low-None, and High-None) and Blocks (all 40 blocks) also confirmed our observation; no significant main effect of Groups ($F(2, 24) = 0.62, p = 0.55, \eta^2p = 0.05$), an expected significant main effect of Blocks ($F(39, 936) = 23.9, p < 0.0001, \eta^2p = 0.5$), indicating visuomotor adaptation. We observed a significant interaction ($F(78, 936) = 1.70, p = 0.0003, \eta^2p = 0.12$), which was led by a higher reach error at the first block for the High-None group than for 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 ($F(2, 24) = 4.93, p = 0.02, \eta^2p = 0.29$). Savings is defined as the difference in reach error between the early adaptation and early recall phases (gray areas in Fig. 2B–D). 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 Fig. 2F, the None-None group (Fig. 2B) showed significantly higher savings than the Low-None (Fig. 2C) and High-None groups (Fig. 2D), who did not differ from each other.

Therefore, we showed that performing the RSVP task concurrently with the visuomotor adaptation task did not impair the immediate motor performance (Fig. 2A). With the parametric manipulation of attentional loads, we replicated and extended what we observed in (Bédard & Song, 2013), in which only the none vs. 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, it could be the case that the inconsistency

of task contexts (single vs. dual) between the adaptation and recall phases disrupted memory retrieval despite the equivalent reduction in error rate during adaptation. We therefore assessed which of the two hypotheses (disruption in memory formation vs. failure in memory retrieval) explains our findings.

Consistent task-contexts between learning and recall is essential for

successful recall—To evaluate these two alternative possibilities, disruption in memory formation vs. failure in memory retrieval, we compared performance of the High-High group, who performed the RSVP task during both the adaptation and the recall phases (consistent dual-task context), with the performance of the None-None (consistent single-task context) and High-None (inconsistent task context) groups. In the High-High group, we confirmed again that the visuomotor adaptation task did not interfere with the performance of the RSVP task (Fig. S1A) across the baseline, adaptation, and recall phases ($F(2, 16) = 0.21, p = 0.81, \eta^2p = 0.02$) and that RSVP performance was similar to that of the High-None group (see Fig. S1A legend for statistical analysis).

During adaptation, the High-High group (Fig. 2E) reduced reach error similarly to the None-None and High-None groups (Fig. 2A), which was confirmed by a two-way ANOVA with Groups (None-None, High-None, and High-High) and Blocks (all 40 blocks) as factors: no main effect of Groups ($F(2, 24) = 0.89, p = 0.42, \eta^2p = 0.07$) and an expected significant main effect of Blocks ($F(39, 936) = 32.4, p < 0.0001, \eta^2p = 0.57$). A significant interaction ($F(78, 936) = 1.69, p = 0.0003, \eta^2p = 0.12$) was driven by a few blocks (blocks 11, 13, and 19) with differences amongst some groups without consistent patterns.

The critical comparison concerns the savings of the High-High group against the None-None and High-None groups (Fig. 2F). If divided attention disrupted memory formation, we should observe little or no savings in the High-High group, much like the High-None group. However, if it is the inconsistency of dual-task contexts between learning and recall that caused interference with memory retrieval in the High-None group, the High-High group should show greater savings than the High-None group and similar savings to the None-None group.

Fig. 2F clearly shows that the High-High group (blue bar), who performed the dual-task throughout both the adaptation and recall phases, had a similar level of savings as the None-None group (black bar) and higher savings than the High-None group (red bar) ($F(2, 24) = 6.91, p = 0.004, \eta^2p = 0.37$). Thus, the attentional division to the RSVP task did not weaken the underlying memory. Instead, these results indicate that the inconsistency of the dual-task 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, as shown in the High-None group with essentially no savings (Fig. 2F, red bar). However, higher savings in the None-None group (Fig. 2F, black bar) shows that full attention to motor performance at recall is not by itself disadvantageous.

To provide converging evidence, we removed task consistency by reversing the High-None group, forming a None-High group. In accord with the notion of task-context dependent memory retrieval, the None-High group did not show significant savings ($t(11) = 0.19, p =$

0.85; means $\pm$ s.e: 0.39 ± 2.04). However, this lack of savings could also be due to the sudden introduction of a dual-task at recall. Thus, this group has weaker diagnostic value because this suddenness introduces a complication not present in the other groups. Thus, we did not include this group in a subsequent experiment.

These results clearly demonstrate that a consistent task context (single vs. dual) influences the recall success of newly acquired visuomotor memories. It is important to note that it is task consistency that is relevant and not the low level consistency of visual stimuli, because the RSVP stream was presented for all experimental phases and for all groups even when RSVP performance was not required. We also ruled out the possibility that a speed-accuracy trade-off caused attentional-state dependent retrieval effects as shown by statistically equivalent RT and MT across all conditions (Figs. S1C–D; see legend for statistical analysis).

In sum, Experiment 1 demonstrates that while diverting attention to the secondary task during adaption does not impair memory formation, inconsistent task contexts (single vs. dual) during adaptation and recall impairs retrieval of visuomotor memories. In Experiment 2, we examined whether it is simply repetition of the same task between adaptation and recall or the consistency of attentional diversion to a secondary task itself that determines the success of memory retrieval.

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 with normal color vision and normal or corrected-to-normal vision participated in our experiments (19–23 years old). All the experimental protocols were approved by the Institutional Review Board at Brown University. Participants received monetary compensation or a course credit.

Tasks—The same visuomotor adaptation task (Fig. 1A) and RSVP task (Fig. 1B) with none and high loads were used as in Experiment 1.

Secondary Brightness discrimination task (Fig. 1C): Five grey squares (1 cm^2) of three different luminance levels (low, mid, high) appeared consecutively 0.5 cm above the starting base with the same timing as the RSVP task and participants had to count the number of low and high luminance squares presented; the reference middle square was presented before each trial. The number of relevant luminance squares varied randomly between 1 and 3 with equal probability, yielding chance level of 33%. Participants reported the number of targets observed (1, 2 or 3) at the end of each trial by pressing a keyboard with their left hand.

Secondary Sound discrimination task (Fig. 1D): Five tones of three different frequencies (low, mid, high) appeared again with the same timing as the RSVP task and participants had to count the number of low or high frequency tones presented. The number of relevant high and low frequency tones varied randomly between 1 and 3 with equal probability.

Participants reported the number of targets observed (1, 2 or 3) at the end of each trial by pressing a keyboard key with their left hand.

Procedure—The procedure was the same as in Experiment 1 except a few modifications. First, we formed five new groups ($N=10$, each): In addition to the None-None, High-None, High-High groups as in Experiment 1, we added the High-Brightness, and High-Sound groups (Fig. 1E). The two new groups performed the same high-load RSVP task during adaptation as in Experiment 1. The important difference about the two new groups is that while a secondary task was also performed at recall, the nature (i.e., the stimuli and the responses required) of the secondary tasks themselves was very different than during adaptation.

Although our previous study has already shown that eye movements are unlikely to affect visuomotor adaptation (Song & Bédard, 2013), we controlled eye movements as a precaution in Experiment 2 because it is possible that our effects in Experiment 1 resulted from different eye movement strategies between groups. We required participants to always maintain gaze within a 1° radius circle around the starting base position for the whole trial duration. We used an eye-tracker (EyeLink II, SR Research; 250 Hz) to monitor gaze position. As soon as gaze was broken, the trial was aborted and repeated immediately to match the number of trials in each group. 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—To assure that the seemingly paradoxical task-context dependent retrieval effect shown in Experiment 1 is a robust and reliable phenomenon, we first replicated results from the None-None, High-None, and High-High groups, while controlling eye movements. As shown in Fig. S2 (see legend for statistical analyses), we confirmed that controlled eye position did not affect our findings in the RSVP task across all the three groups, though in general, the fixation requirement lowered RSVP accuracy. This result is likely because of the added difficulty of performing the task using peripheral vision. We also replicated the pattern of visuomotor adaptation (Fig. 3A–C). All three groups decreased reaching error similarly across the whole adaptation phase as confirmed by an ANOVA that revealed no significant main effect of Groups, an expected main effect of Blocks (all 40 blocks), and a significant interaction ($F(2, 27) = 0.97$, $p = 0.39$, $\eta^2p = 0.07$; $F(39, 1053) = 78.8$, $p < 0.0001$, $\eta^2p = 0.74$, and $F(78, 1053) = 1.77$, $p < 0.0001$, $\eta^2p = 0.11$, respectively). The interaction was due to a few blocks (blocks 2 and 7) with differences between groups but without a consistent pattern.

Critically, regarding savings (Fig. 3F), we replicated Experiment 1 in that the None-None and High-High group had higher savings than the High-None group ($F(2, 27) = 5.2$, $p = 0.01$, $\eta^2p = 0.28$). Thus, we reliably re-established our observed paradoxical enhancement at recall with consistent dual-task contexts, regardless of eye movement strategies. To further assure the robustness of task context-dependent memory retrieval, we replicated results

again in a separate within-participants design ($N=10$), again obtaining converging evidence (See, Fig. S3 for details and statistical analyses).

Reinstatement of task-contexts across different task requirements and sensory modalities

The primary goal of Experiment 2 was to determine whether the key to successful visuomotor memory retrieval is to repeat the same 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 requirement or sensory modality, then the High-Brightness and High-Sound groups, who divided their attention to different secondary tasks during adaptation and recall, should have similar savings as the None-None and High-High groups, who repeated the same secondary task, and more savings than the High-None group.

As in the None-None, High-None, and High-High groups (Figs. 3A–C), both the High-Brightness and High-Sound groups (Figs. 3D–E) reduced reach error during the adaptation phase, which was confirmed by a two-way ANOVA: no significant main effects of Groups ($F(4, 45) = 0.46, p = 0.77, \eta^2p = 0.04$), and an expected main effect of Blocks ($F(39, 1755) = 130.05, p < 0.0001, \eta^2p = 0.74$). A significant interaction led by a few blocks (1 and 12) without a consistent pattern was observed ($F(156, 1755) = 1.31, p = 0.008, \eta^2p = 0.10$).

Very interestingly, Figure 3F shows indistinguishable savings for the High-Brightness and High-Sound groups compared to the None-None and High-High groups, and savings in all these groups were higher than savings in the High-None group ($F(4, 45) = 2.77, p = 0.04, \eta^2p = 0.20$). Thus, the successful savings during recall cannot be attributed to task specificity or sensory similarity between learning and recall. Rather, the consistency of abstract task-contexts (single vs. dual) from adaptation to recall can overcome changes in the secondary task (e.g., task requirement and sensory modality) and ensure proper memory recall.

Discussion

In accord with the well-recognized capacity limit view of attention, it has been assumed that concurrently performing 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 (High-High) or undivided (None-None) to a secondary task, recall performance was high. On the other hand, 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 where 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.

This phenomenon differs from previous studies on episodic memory, in which divided attention to a secondary task at encoding significantly reduces subsequent memory

performance, whereas divided attention at retrieval affects memory performance only minimally. This asymmetry suggests shared resources for attention and episodic memory during encoding, but not retrieval (Anderson et al., 2000; Fletcher et al., 1995; Naveh-Benjamin, Guez, & Marom, 2003; Rohrer & Pashler, 2003). We propose that divided attention to a secondary task plays a distinct role for 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, it has been shown that the success of episodic memory retrieval depends on whether or not the coincidental environmental context at the time of learning is reinstated at recall (Smith & Vela, 2001; Godden & Baddeley, 1975). On the surface, this reinstatement of environmental contexts in episodic memory retrieval appears to operate similarly to what we have observed here. Yet, in contrast to prior studies on episodic memory (Eich, 1980), in which consistent external contextual cues have a priority over consistent internal states for memory retrieval, 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, or sound discrimination) or rely on the same sensory modality in order to reinstate the task contexts for motor memory recall. Therefore, the role of task-context appears to substantially outweigh the role of environmental context in the effective retrieval of learned motor skills.

In addition to the external context, 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 or a dual-task 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 the current study relate to our understanding of motor learning? According to a representative model of motor learning, two distinct processes operating on different timescales 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; Smith, Ghazizadeh, & Shadmehr, 2006). In the present results, we found no differences in motor error reduction or memory formation, which indicates equivalent involvement of fast and slow processes. Yet, we still found impairment of memory retrieval by the inconsistent task-contexts. Thus, the two-process model solely based on error-based learning needs to be updated to account for cognitive effects such as robust task-context modulation on 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 is still in question (Andersen, Hwang, & Mulliken, 2009; Kitago & Krakauer, 2013). The present study enhances our understanding of how task context, meaning whether the availability of attentional resources is consistent from motor memory formation to recall, gates the stability of visuomotor learning. We demonstrate that without consideration of internal task contexts in real life situations, the stability of learning and rehabilitation programs may be undermined. This new discovery of task context-dependent memory indicates that visuomotor learning processes can only be fully understood by updating current models of attention, motor learning, and memory.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

- Andersen RA, Hwang EJ, Mulliken GH. Cognitive neural prosthetics. *Annu Rev Psychol.* 2009; 61:169–190. C161–163. [PubMed: 19575625]
- Anderson ND, Iidaka T, Cabeza R, Kapur S, McIntosh AR, Craik FI. The effects of divided attention on encoding- and retrieval-related brain activity: A PET study of younger and older adults. *J Cogn Neurosci.* 2000; 12(5):775–792. [PubMed: 11054920]
- Bédard P, Song J-H. Attention modulates generalization of visuomotor adaptation. *J Vis.* 2013; 13(12): 12. [PubMed: 24133292]
- Blasi V, Young AC, Tansy AP, Petersen SE, Snyder AZ, Corbetta M. Word retrieval learning modulates right frontal cortex in patients with left frontal damage. *Neuron.* 2002; 36(1):159–170. [PubMed: 12367514]
- Cohen, J. *Statistical Power Analysis for the Behavioral Sciences.* 2. New Jersey: Lawrence Erlbaum Associates; 1988.
- Brainard DH. The Psychophysics Toolbox. *Spat Vis.* 1997; 10(4):433–436. [PubMed: 9176952]
- Courneya KS, Carron AV. The Home Advantage in Sport Competitions - a Literature-Review. *Journal of Sport & Exercise Psychology.* 1992; 14(1):13–27.
- Curran T, Keele SW. Attentional and nonattentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition.* 1993; 19(1):189–202.
- DeCarli C, Haxby JV, Gillette JA, Teichberg D, Rapoport SI, Schapiro MB. Longitudinal changes in lateral ventricular volume in patients with dementia of the Alzheimer type. *Neurology.* 1992; 42(10):2029–2036. [PubMed: 1407587]
- Eich JE. The cue-dependent nature of state-dependent retrieval. *Mem Cognit.* 1980; 8(2):157–173.
- Fletcher PC, Frith CD, Grasby PM, Shallice T, Frackowiak RS, Dolan RJ. Brain systems for encoding and retrieval of auditory-verbal memory. An in vivo study in humans. *Brain.* 1995; 118(Pt 2):401–416. [PubMed: 7735882]
- Goodwin DW, Powell B, Bremer D, Hoine H, Stern J. Alcohol and recall: state-dependent effects in man. *Science.* 1969; 163(3873):1358–1360. [PubMed: 5774177]

- Joiner WM, Ajayi O, Sing GC, Smith MA. Linear hypergeneralization of learned dynamics across movement speeds reveals anisotropic, gain-encoding primitives for motor adaptation. *J Neurophysiol.* 2011; 105(1):45–59. [PubMed: 20881197]
- Joseph JS, Chun MM, Nakayama K. Attentional requirements in a ‘preattentive’ feature search task. *Nature.* 1997; 387(6635):805–807. [PubMed: 9194560]
- Khan AZ, Song J-H, McPeck RM. The eye dominates in guiding attention during simultaneous eye and hand movements. *J Vis.* 2011; 11(1):1–14.
- Kitago T, Krakauer JW. Motor learning principles for neurorehabilitation. *Handb Clin Neurol.* 2013; 110:93–103. [PubMed: 23312633]
- Krakauer JW, Ghez C, Ghilardi MF. Adaptation to visuomotor transformations: consolidation, interference, and forgetting. *J Neurosci.* 2005; 25(2):473–478. [PubMed: 15647491]
- Krakauer JW, Pine ZM, Ghilardi MF, Ghez C. Learning of visuomotor transformations for vectorial planning of reaching trajectories. *J Neurosci.* 2000; 20(23):8916–8924. [PubMed: 11102502]
- Naveh-Benjamin M, Guez J, Marom M. The effects of divided attention at encoding on item and associative memory. *Mem Cognit.* 2003; 31(7):1021–1035.
- Nishimura M, Shiigi Y, Kaneto H. State dependent and/or direct memory retrieval by morphine in mice. *Psychopharmacology (Berl).* 1990; 100(1):27–30. [PubMed: 2296624]
- Nissen MJ, Bullemer P. Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology.* 1987; 19(1):1–32.
- Pelli DG. The VideoToolbox software for visual psychophysics: transforming numbers into movies. *Spat Vis.* 1997; 10(4):437–442. [PubMed: 9176953]
- Peters R, Mcgee R. Cigarette-Smoking and State-Dependent Memory. *Psychopharmacology.* 1982; 76(3):232–235. [PubMed: 6808542]
- Raymond JE, Shapiro KL, Arnell KM. Temporary suppression of visual processing in an RSVP task: an attentional blink? *J Exp Psychol Hum Percept Perform.* 1992; 18(3):849–860. [PubMed: 1500880]
- Rohrer D, Pashler HE. Concurrent task effects on memory retrieval. *Psychon Bull Rev.* 2003; 10(1):96–103. [PubMed: 12747495]
- Smith MA, Ghazizadeh A, Shadmehr R. Interacting adaptive processes with different timescales underlie short-term motor learning. *Plos Biology.* 2006; 4(6):1035–1043.
- Smith SM, Vela E. Environmental context-dependent memory: a review and meta-analysis. *Psychon Bull Rev.* 2001; 8(2):203–220. [PubMed: 11495110]
- Song J-H, Bédard P. Allocation of attention for dissociated visual and motor goals. *Exp Brain Res.* 2013; 226(2):209–219. [PubMed: 23417647]
- Taylor JA, Thoroughman KA. Divided attention impairs human motor adaptation but not feedback control. *J Neurophysiol.* 2007; 98(1):317–326. [PubMed: 17460104]
- Taylor JA, Thoroughman KA. Motor adaptation scaled by the difficulty of a secondary cognitive task. *PLoS One.* 2008; 3(6):e2485. [PubMed: 18560546]
- Wu HG, Smith MA. The generalization of visuomotor learning to untrained movements and movement sequences based on movement vector and goal location remapping. *J Neurosci.* 2013; 33(26):10772–10789. [PubMed: 23804099]

Task schematics. **A:** Reaching task. Reach targets appeared one at a time and remained visible for the entire trial (1500 ms). In null trials, the cursor followed stylus motion normally, whereas in rotation trials, the cursor direction was rotated by 45° CCW from the reach trajectory. **B–D:** Secondary tasks. Five upright or inverted ‘T’s of various colors (B), five grey squares (1 cm²) of three different luminance levels (low, mid, high) (C), or five tones of three different frequencies (low, mid, high) (D) sequentially appeared for 150 ms with 150 ms gaps (total 1500 ms) in the RSVP tasks. In all tasks, participants had to report how many targets (1, 2 or 3) were presented in a sequence by pressing a keyboard key at the end of each trial with their left hand. Targets were defined by a single (e.g., low load: green T) or conjunction feature (e.g., high load: upright red and inverted green T) in the RSVP task (B), the low and high luminance squares in the brightness detection task (C) and the low and high frequency tones in the sound detection task (D). **E:** Secondary task performed in each group throughout each experimental phase.

Figure 2.

Reach error (**A–E**) during the visuomotor adaptation task (averaged over blocks of 4 trials; mean $\pm$ SE; $N = 9$ in each group) and savings (**F**) in Experiment 1. **A**: Reaching error for None-None, Low-None, High-None, and High-High groups during the adaptation phase. All groups performed similarly regardless of attentional load. **B–E**: Reach error during the adaptation (open circle) and recall phases (solid circle) for the None-None (**B**), Low-None (**C**), High-None (**D**), and High-High groups (**E**). Gray areas in each figure indicate which blocks were used to calculate savings. **F**: Savings for the None-None, Low-None, High-None, and High-High groups. Only the None-None and High-High groups showed significant savings during recall.

Figure 3.

Reach error (**A–E**) during the visuomotor adaptation task (averaged over blocks of 4 trials; mean $\pm$ SE; $N = 10$ in each group) and savings (**F**) in Experiment 2. Eye fixation was required within a 1° radius centered on the starting base. **A–E**: Reach error during the adaptation (open circle) and recall phases (solid circle) for the None-None (**A**), High-None (**B**), High-High (**C**), High-Brightness (**D**), and High-Sound groups (**E**). Gray areas in each figure indicate which blocks were used to calculate savings. **F**: Savings for the None-None, High-None, High-High, High-Brightness and High-Sound groups. The magnitude of savings was significantly higher for the None-None, High-High, High-Brightness, and High-Sound groups than for the High-None group.