Journal of Experimental Psychology:
Human Perception and Performance
2016, Vol. 42, No. 9, 1269–1274

0096-1523/16/$12.00 http://dx.doi.org/10.1037/xhp0000271

OBSERVATION

Long Lasting Attentional-Context Dependent Visuomotor Memory

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Using a dual-task paradigm, we recently reported that visuomotor adaptation acquired under distraction of a secondary attention-demanding discrimination task could be remembered only when a similar distraction was present. In contrast, when tested without the distracting task, performance reverted to untrained levels (Song & Bédard, 2015). Here, we demonstrated that this newfound paradoxical benefit of consistent dual-task context lasts over 1 day, such that visuomotor memory retrieval is enhanced under conditions where it is more difficult to engage in attentional selection of the motor task. Furthermore, this long-term effect was evident even when the task type or sensory modality of the secondary task differed between initial adaptation and the delayed recall on the next day. We conclude that attentional diversion by performing a dual-task forms a long-term vital *context* for visuomotor memory independent of external contexts without taxing capacity limited attention.

Keywords: visuomotor learning, attentional-context, memory retrieval

Successfully executing visuomotor skills while attention is distracted by other events or stimuli is essential for everyday activities. For instance, during an aircraft emergency, a pilot must continue to operate the aircraft while maintaining interactions with crew members. A stroke patient recovering the ability to walk in a rehabilitation session faces similar challenges as she must divide her attention to avoid collisions with any obstacles while walking. In both cases, attentional distractions interfere with the primary goal of executing acquired motor skills.

Because attention is a necessary resource for cognitive functions, dividing attentional resources across tasks can greatly impair motor performance (Pashler, 1998), including sequence motor learning (Curran & Keele, 1993; Nissen & Bullemer, 1987) and sensorimotor adaptation (Taylor & Thoroughman, 2007, 2008). However, we recently showed that high attentional load does not interfere with visuomotor adaptation, but in fact paradoxically benefits retrieval of visuomotor memory when the attentional distraction remains consistent during learning and recall. These results suggest that attention serves an unexpected role in selecting external sensory stimuli and integrating them with motor memory without taxing attention capacity. Attentional contexts in turn gate memory retrieval by serving as an internal “vital context” (Im, Bédard, & Song, 2015; Song & Bédard, 2015).

How long would the attentional context induced by dual-task context last for visuomotor memory retrieval? Previous studies (e.g., Song & Bédard, 2015) have reported its immediate effects by measuring recall performance shortly after the learning phase. Here, we examined whether attentional context is only encoded into short-term memory (STM) or it transfers to long-term memory. If attentional context that is integrated with visuomotor memory during learning on the first day transfers to long-term memory, then recall of this newly acquired visuomotor skill on the following day should be facilitated, but only when attentional context remains consistent on both days (i.e., between learning and recall). Furthermore, if it is attentional-context itself that is maintained in long-term memory, rather than episodic memory of a specific second task, then we would observe the same facilitation on the second day even when tested in different tasks or with different sensory modalities, as long as the attentional context remains consistent.

This article was published Online First July 25, 2016.

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This project was supported by NIGMS-NIH IDeA P20GM103645 and the Rhode Island Foundation to Joo-Hyun Song. Hee Yeon Im was partially supported by the postdoc fellowship from the Center for Vision Research at Brown University.

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Method

Detailed methods were largely adapted from Song & Bédard (2015) with one critical modification to measure a long-term effect of attentional context on visuomotor memory retrieval.

Participants

A total of 50 right-handed participants with normal color vision and normal or corrected-to-normal visual acuity participated for monetary compensation or course credit. The number of participants per group ($n = 10$) was determined based on our prior studies, which used a similar dual-task paradigm and experimental design (Bédard & Song, 2013; Im et al., 2015; Song & Bédard, 2015), resulting in reliably large effect sizes (Cohen, 1988) as indexed by partial eta squared ($\eta_p^2 > 0.26$). It is consistent with reported sample sizes from similar visuomotor adaptation studies by various groups (e.g., Krakauer, Ghez, & Ghilardi, 2005; Taylor & Thoroughman, 2007; Wu & Smith, 2013). All the experimental protocol was approved by the Institutional Review Board (IRB) at Brown University.

Apparatus

Participants sat in a chair about 57 cm away from an Apple iMac computer with a 21-in. screen (refresh rate = 60 Hz), holding a stylus pen in the right hand. The tip of the stylus rested on a touch screen (Magic Touch; Keytec) that lay flat on a table and aligned with each participant's midline and the center of the monitor. We presented visual stimuli and recorded cursor displacement using MATLAB and functions from PsychToolbox (Brainard, 1997; Pelli, 1997).

Visuomotor Adaptation Task

In the primary task, participants had to move a cursor from a starting base (annulus with a diameter of 1°, corresponding to 1 cm) in the center of the screen toward visible reach targets (1° diameter) located 5.5 cm away at 3, 6, 9, and 12 o'clock in relation to the starting base. 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. There were two types of trials. In null trials, the cursor followed stylus motion normally; in rotation trials, the cursor direction was rotated 45° counterclockwise to force movement adaptation (Figure 1A). After 40 practice trials with no cursor perturbation, each participant performed four sequential experimental phases in two consecutive days: *on the first day,* the baseline (80 null trials), adaptation (160 rotation trials), and deadaptation (80 null trials) phases and on *the second day,* the recall phase (80 rotation trials).

Secondary Tasks

On 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 Rapid Serial Visual Presentation (RSVP) task (Figure 1B), five upright or inverted T's were presented in various colors. In the brightness discrimination task (Figure 1C), five gray 1 cm^2 squares of low, medium, or high luminance were presented. In the sound discrimination task (Figure 1D), five tones of low, medium, or high frequency are presented. For all secondary tasks, participants reported how many relevant targets (one, two, or three) were presented at the end of each trial. Targets were defined by (1) a conjunction feature (e.g., upright red and inverted green T) in the RSVP Task, (2) low and high luminance squares in the brightness discrimination task, and (3) low and high frequency tones in the sound discrimination task. When participants did not perform the secondary task, they were also required to press a key in response to a visual cue at the end of each trial (e.g., "Press button 1"). Visual or auditory stimuli appeared on every trial of all experimental phases in order to maintain the consistency of exposure to the external stimuli across all participants and condition. This also ensured that attentional context was not confounded with low-level consistency of external stimuli.

Procedure

All participants performed the visuomotor adaptation task (Figure 1A), but the performance of the secondary task (Figure 1B–

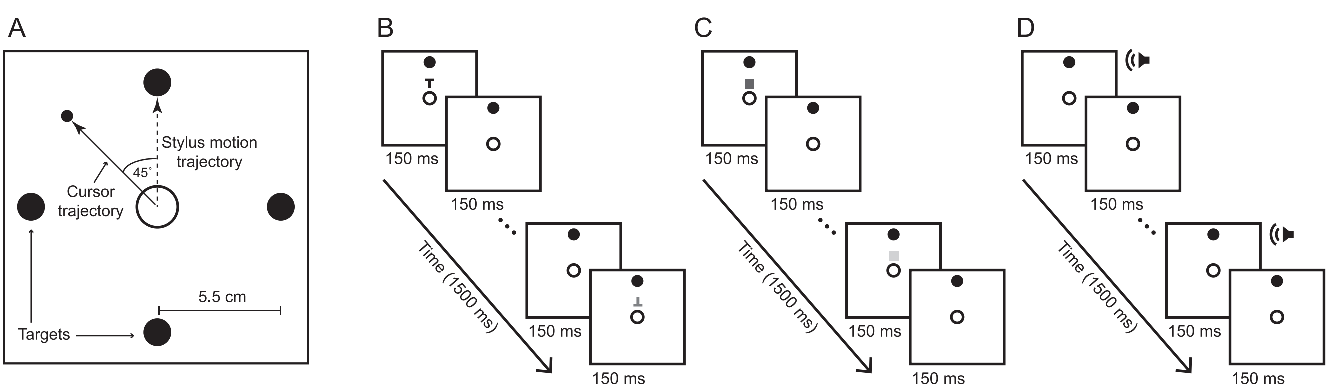

Figure 1. Task schematics. Reaching task (A). Reach targets appeared one at a time and remained visible for the entire trial (1,500 ms). In null trials, the cursor followed stylus motion normally, whereas in rotation trials, the cursor direction was rotated by 45° counter-clockwise (CCW) from the reach trajectory. Secondary tasks (B–D). Five upright or inverted Ts of various colors (B), five gray squares (1 cm^2) 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 1,500 ms) in the Rapid Serial Visual Presentation (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., 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).

1D) depended on the group assignment and the experimental phase (see Table 1). We randomly assigned participants to one of five groups (n = 10 per group), labeled according to the secondary tasks during the adaptation and recall phases: none-none, rsvp-none, rsvp-rsvp, rsvp-brightness, and rsvp-sound.

Data Analysis and Statistics

We measured reaching 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. We averaged the reaching error across each block of four trials. We measured savings, a metric of memory formation, by calculating the average reach error in the early adaptation and the early recall phases (e.g., Blocks 3 to 8) and then taking the difference between these averages, as in previous work (Im et al., 2015; Song & Bédard, 2015).

Results

No Interference by the Secondary Task

As shown in Figure 2, participants of all the four groups performed the secondary task significantly better than chance (33%, all p values < 0.01). In accord with our prior studies (Im, Bédard, & Song, 2015; Song & Bédard, 2015), one-way analyses for variance (ANOVAs) for each group confirmed that there was no accuracy difference across the phases (rsvp-none: $F(1, 18) = 0.06$, $p = .81$, $\eta^2 = 0.015$; rsvp-rsvp: $F(2, 27) = 0.36$, $p = .70$, $\eta^2 = 0.014$; rsvp-brightness: $F(2, 27) = 1.14$, $p = .34$, $\eta^2 = 0.109$; rsvp-sound: $F(2, 27) = 0.40$, $p = .68$, $\eta^2 = 0.029$), suggesting that visuomotor rotational adaptation does not interfere with visual or auditory detection (Khan, Song, & McPeek, 2011).

Next, we compared the reaching error of all the five groups during the adaptation phase, to examine whether attentional diversion to the secondary task disrupted reaching performance. In all groups, we observed that reach errors were reduced across trials and the level of performance was similar across groups by the end of the adaptation phase (Figure 3A). A two-way ANOVA with groups (none-none, rsvp-none, rsvp-rsvp, rsvp-brightness, and rsvp-sound) and blocks (all 40 blocks) confirmed this: no significant main effect of groups, $F(4, 45) = 0.93$, $p = 0.46$, $\eta^2 = 0.116$, an expected significant main effect of blocks, $F(39, 1{,}800) = 65.08$, $p < .01$, $\eta^2 = 0.319$, indicating visuomotor adaptation, and no significant interaction, $F(156, 1{,}800) = 0.90$, $p = .79$, $\eta^2 = 0.084$. This result is also consistent with our prior studies (Bédard

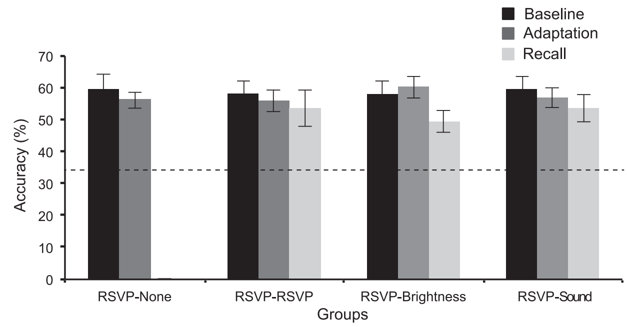

Figure 2. Average accuracy for the secondary tasks of each group (rsvp-none, rsvp-rsvp, rsvp-brightness, and rsvp-sound) during baseline, adaptation, and recall phases. The dotted line indicates the 33% chance level. The error bars indicate the standard error of the means (SEM). RSVP = Rapid Serial Visual Presentation.

& Song, 2013; Im et al., 2015; Song & Bédard, 2015), suggesting that divided attention does not impair immediate motor performance and that visuomotor rotational adaptation does not cause additional interference in visual or auditory detection and vice versa. Therefore, these results confirm that all the groups acquired the visuomotor memory to the equivalent levels.

Long-Lasting Effect of Attentional-Context Dependent Memory Across Different Tasks and Modalities

To evaluate the long-term benefits of consistent attentional context on visuomotor memory (Song & Bédard, 2015), we compared savings in reaching error during recall between Day-1 and Day-2 for each of the five groups. Savings were calculated as the difference in reaching error between the initial trials of the adaptation and recall phases (e.g., blocks 3–8; gray shaded areas in Figure 3B–3F). Larger savings indicate enhanced recall performance. Figure 3G shows that the savings effect was reduced in the rsvp-none group compared with the other groups. A one-way ANOVA confirmed this observation, $F(4, 45) = 3.23$, $p < .05$, $\eta^2 = 0.229$, and post hoc t tests indicated that the four attentional-context consistent groups (none-none, rsvp-rsvp, rsvp-brightness, and rsvp-sound) showed significantly larger savings than the inconsistent, rsvp-none group (all p values $< .05$). We found no significant difference in savings across the four attentional-context consistent groups, $F(3, 36) = 0.36$, $p = .78$, $\eta^2 = 0.077$. To confirm

Table 1
Secondary Tasks Performed by the Groups

Groups	Day 1 Baseline	Day 1 Adaptation	Day 1 Deadaptation	Day 2 Recall
None-None	X	X	X	X
RSVP-None	RSVP	RSVP	X	X
RSVP-RSVP	RSVP	RSVP	X	RSVP
RSVP-Brightness	RSVP	RSVP	X	Brightness discrimination
RSVP-Sound	RSVP	RSVP	X	Sound discrimination

Note. RSVP = Rapid Serial Visual Presentation.

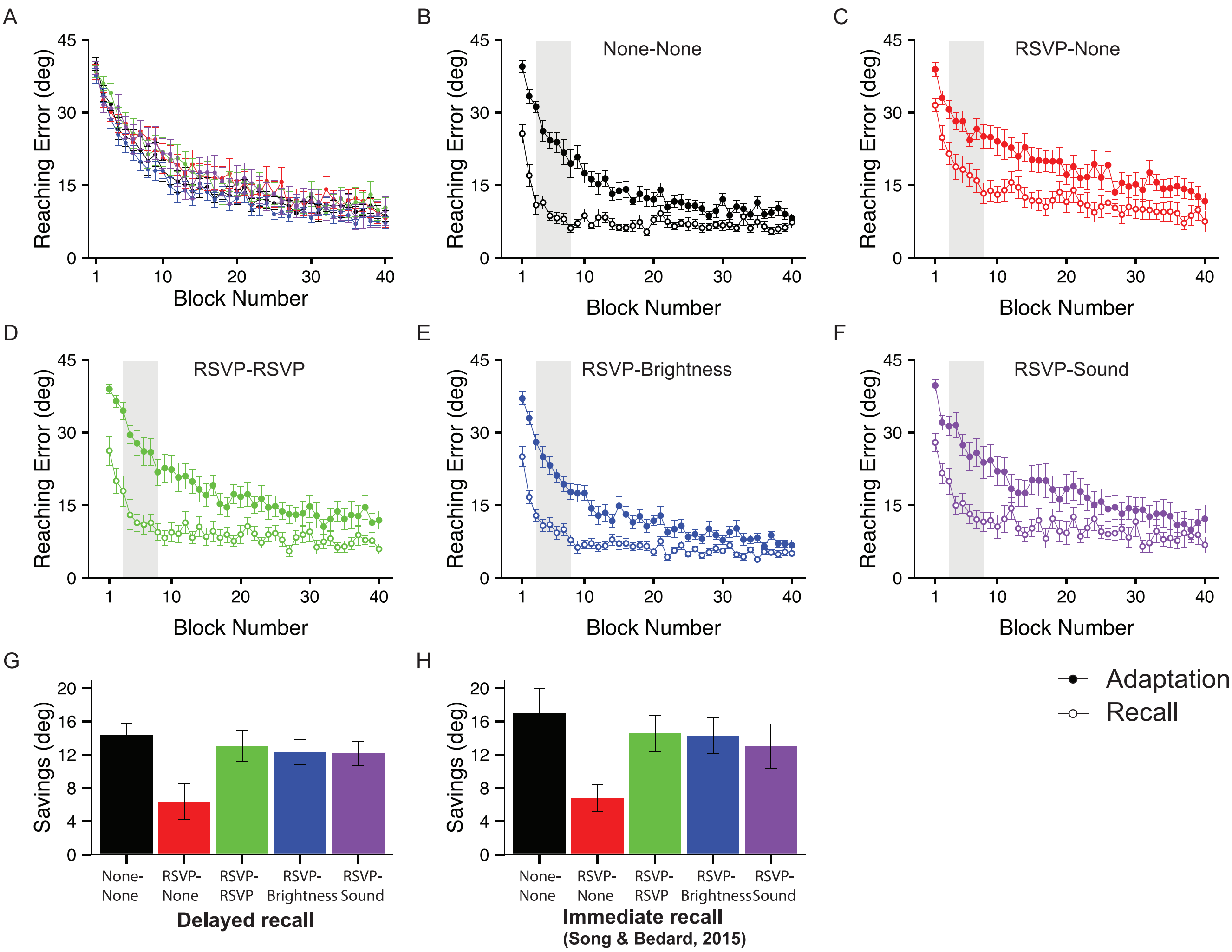

Figure 3. Performance of all five groups during the learning and recall phases of the visuomotor learning task (A–F) and magnitude of savings (G–H). The error bars indicate the standard error of the means (SEM). Reaching error during the adaptation phase for all the five groups overlapped with each other (A). This plot confirms no qualitative difference in acquisition of visuomotor memory across the groups during the adaptation phase. Reaching error during the adaptation (open square) and recall (solid square) phases for none-none (B), rsvp-none (C), rsvp-rsvp (D), rsvp-brightness (E), and rsvp-sound (F) groups. Gray areas in each figure indicate the blocks (3–8) that were used to calculate savings shown in (G). Savings for all five groups (G). Savings from the same five groups who performed the adaptation and recall phases on the same day (immediate recall; H). This is a part of the published data in Song & Bédard (2015). RSVP = Rapid Serial Visual Presentation. See the online article for the color version of this figure.

that the reported measure of savings are reliable and robust, we varied the ranges of the blocks (e.g., Blocks 1–2, 1–40) and calculated savings, respectively for each group. One-way ANOVA revealed that all the four attentional-context consistent groups (e.g., none-none, rsvp-rsvp, rsvp-brightness, and rsvp-sound) yielded consistently higher savings than the attentional-context inconsistent group (e.g., rsvp-none; all p values $<$ .001). These results suggest that consistent attentional context is maintained and generalized across different task demands or sensory modality, improving visuomotor memory recall. Since the effect of consistent attentional context lasted at least one day after initial adaptation, attentional context appears to be integrated into long-term motor memory.

Immediate Versus Delayed Recall

To evaluate whether a 1-day delay affected recall, we directly compared savings from the current study to those from Song & Bédard (2015), in which the same five groups were tested immediately for recall on the same day. As shown in Figure 3H, savings from the immediate recall (Song & Bédard, 2015) did not differ from those from the delayed recall. A two-way ANOVA with groups (none-none, rsvp-none, rsvp-rsvp, rsvp-brightness, and rsvp-sound) and recall types (immediate and delayed) confirmed our observation: a significant main effect of groups, $F(4, 45) = 3.48$, $p < .05$, $\eta^2 = 0.393$, but no significant main effect of the recall types, $F(1, 90) = 0.43$, $p = .52$, $\eta^2 = 0.081$, and no significant interaction, $F(4, 90) = 0.46$, $p = .77$, $\eta^2 = 0.062$. This result suggests that the attentional context benefit on recall performances persists for at least one day.

Discussion

Our series of recent work (Im et al., 2015; Song & Bédard, 2015), we discovered that successful recall of the visuomotor skill only occurred when a similar level of attentional distraction was present during encoding and recall. This attentional-context dependent "savings" was robust even when the specific task type or sensory modality differed between the adaptation and recall phases. Thus, these results suggest that the primary role of attention is in selecting and associating external sensory stimuli with motor memory rather than in providing capacity-limited resource for learning. It also implies that what is encoded into motor memory is not the specific physical parameters of distracting stimuli.

The current study extended our prior attentional-context dependent memory retrieval to a long-term memory domain. We showed that visuomotor adaptation yields long-term savings in the none-none group in accord with previous motor learning studies (e.g., Flanagan, Bittner, & Johansson, 2008; Gordon, Westling, Cole, & Johansson, 1993; Huberdeau, Haith, & Krakauer, 2015). We further showed that consistent dual-task contexts modulate motor memory retrieval for at least a day after initial learning, and it does not rely on the repetition of the same stimulus context. Therefore, familiar context repetition appears to provide a long-term benefit for revealing past learning, even with distraction during encoding.

Similar to our findings, the previous studies have showed that past experience of a specific attentional set and strategy even during a brief exposure can lead to a long-lasting influence on one's strategy and attentional set (Leber & Egeth, 2006; Leber, Kawahara, & Gabari, 2009; Thompson, Underwood, & Crundall, 2007). Such long-lasting learning effect by past experience of attentional set has been discussed as automatic activation of association formed between attentional sets and the environmental contexts (Cooper & Shallice, 2000; Norman & Shallice, 1986; see also Logan, 1988). Thus, our findings of paradoxical, long-lasting facilitation by divided attention can be attributed to the association of attentional state (e.g., divided or undivided) and the visuomotor learning context.

On the surface, the reinstatement of attentional context in visuomotor memory appears to operate similarly to the reinstatement of environmental context in episodic memory (Godden & Baddeley, 1975; Smith, 1988; Smith & Vela, 2001). However, our results differ from those on episodic memory in some aspects. First, performing a secondary task interferes with episodic memory performance only at encoding, but not at retrieval, suggesting that attention and episodic memory share resources during encoding but not retrieval (Anderson, 2000; Fletcher et al., 1995; Naveh-Benjamin, Guez, & Marom, 2003; Rohrer & Pashler, 2003). On the contrary, the current study showed that the secondary task in fact facilitates the performance at retrieval when the attentional context remains consistent with the encoding phase. Thus, it seems that deployment of attentional resource merely interferes with a central resource for episodic memory processes, whereas it is integrated as an internal task-context cue for visuomotor memory formation. Second, we showed that the effect of consistent attentional context could be generalized across different task types and sensory modalities, suggesting that attentional context substantially outweighs environmental context for the effective retrieval of visuomotor memory, unlike episodic memory which relies on specific environment.

Conclusion

Here we showed the long-lasting effects of consistent attentional-context on visuomotor memory retrieval, after a relatively short exposure to a combination of novel tasks. If such arbitrary association of attentional context and visuomotor memory persists beyond the 1-hr experimental session, it is likely that associations formed during motor learning outside the lab in the real world would also have a durable time course to significantly benefit everyday motor learning performance (e.g., a stroke patient's practicing to walk). Therefore, the current study provides better practical implications for developing and improving training programs for motor skills by showing that consistency of attentional-context during learning and recall facilitates retrieval and maintenance of visuomotor memory.

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Received August 31, 2015
Revision received February 5, 2016
Accepted May 13, 2016 ■