# Inconsistent attentional contexts impair re-learning following gradual visuomotor adaptation

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**Abstract**

One of the brain's primary functions is to promote actions in dynamic, distracting environments. Because distractions divert attention from our primary goals, we must learn to maintain accurate actions under sensory and cognitive distractions. Visuomotor adaptation is a learning process that restores performance when sensorimotor capacities or environmental conditions are abruptly or gradually altered. Prior work showed that learning to counteract an abrupt perturbation under a particular attentional context created by a single or dual-task setting was associated with better recall under the same attentional context. This suggested that the attentional context was encoded during adaptation and used as a recall cue. The current study investigated whether attentional context (i.e., single vs. dual-task) also affected visuomotor adaptation to a gradual perturbation which limited awareness of movement errors. During adaptation, participants moved a mouse cursor to a target while learning to counteract a cursor rotation that increased from 0 to 45 deg by 0.3 deg each trial, with or without performing a secondary task. The recall was impaired when participants performed the primary task in the attentional context different from adaptation (Experiment 1), even when they were exposed to the attentional context only during the early or late half of adaptation (Experiment 2). Changing the secondary task did not affect recall, indicating that dual-tasking, rather than specific stimuli or tasks, created an attentional context for visuomotor adaptation (Experiment 3). These findings highlight the importance of cognitive factors, such as attention, in visuomotor adaptation and have implications for learning and rehabilitation paradigms.

New & Noteworthy:

Adaptation acquired under single or dual-task conditions, which created attentional contexts -divided or undivided, respectively- was impaired when re-learning occurred under different conditions (e.g., shifting from a dual to a single task).

Changes to the attentional context impaired re-learning when the initial adaptation occurred in response to a gradual perturbation. Explicit awareness of the perturbation was not necessary for this effect to be robust, nor was the effect attributable to changes in the secondary task requirements.

Keywords: visuomotor adaptation, attention, dual task, learning, reaching

## Introduction

Sensorimotor adaptation is essential for everyday activities, allowing us to recalibrate movements as we become familiar with new prescription glasses or tools and as our body undergoes neuromuscular and biomechanical changes. The associative relationships between perception and action have been studied extensively in experimental settings (e.g., Godschalk et al., 1981; Kalaska et al., 1989; Krakauer et al., 2000; Shadmehr et al., 2010). For instance, previous studies suggest that motor errors perceived through visual feedback are used to update and adjust future motor commands, suggesting the roles of sensory feedback signals in selecting actions and improving motor control (Herzfeld et al., 2014; Krakauer et al., 2005; Smith et al., 2006). Reinforcement learning models highlight processes that select the aiming direction of goal-directed movements while maximizing reward outcomes (Pekny et al., 2015; Shmuelof et al., 2012). Although these models acknowledge the connections between perception and action, they overlook how cognitive processes, such as attention, influence sensorimotor adaptation.

Attention is crucial for preparing and generating goal-directed movements when multiple sensory distractors are present (e.g., Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Khan et al., 2010; Kowler et al., 1995). Previous work showed that concurrently performing a secondary attention-demanding task during motor sequence learning or sensorimotor adaptation impaired performance (e.g., Lang & Bastian, 2002; Nissen & Bullemer, 1987; Redding et al., 1992; Taylor & Thoroughman, 2007, 2008). For instance, performing a secondary task while adapting to transient force perturbations interfered with the encoding and

transformation of error signals used to update internal models (Taylor & Thoroughman, 2007). Moreover, sensorimotor adaptation was differentially impaired by the burdens placed on attention and executive control depending on the secondary task difficulty (Taylor & Thoroughman, 2008). Thus, concurrent secondary tasks are presumed to have immediate, detrimental effects on sensorimotor adaptation and task performance.

However, our previous work in young (e.g., Im et al., 2015, 2016; Song, 2019; Song & Bédard, 2015; Wang & Song, 2017) and older adults (Wang et al., 2022) demonstrated that visuomotor adaptation was recalled better and faster when concurrently performing a secondary task (dual task) compared to performing the visuomotor task alone (single task) if the initial adaptation occurred in a dual task context. This is counterintuitive because re-learning was impaired when the attentional demand was reduced by removing the secondary task. Similar decrements were observed after switching from a dual to single task context when attempting to generalize visuomotor adaptation to untrained reach directions (Wang & Song, 2017) and remained up to 24 hours following the initial exposure (Im et al., 2016). These findings led us to postulate that the attentional context—i.e., whether attention was divided and simultaneously allocated to two separate tasks—serves as a contextual cue for the recall of visuomotor adaptation.

Our previous work investigating the integration of the attentional context and visuomotor adaptation employed an abrupt 45 deg perturbation that was introduced and maintained throughout adaptation and recall (e.g., Im et al., 2015, 2016; Song & Bédard, 2015; Wang & Song, 2017). Im et al. (2015) showed that the

attentional context was associated with visuomotor adaptation during the early stage of learning (i.e., the first half of trials) when movement errors rapidly decreased, and when cognitive strategies for counteracting the perturbation are most likely to be employed (Taylor et al., 2014). By contrast, when actions become more automated and dependent on repetition (Orban de Xivry et al., 2011) and attentional control is reduced (Atkeson, 1989; Fitts & Posner, 1967; Preilowski, 1977), the attentional context experienced during the late stage of learning (i.e., the second half of trials) was not associated with visuomotor adaptation. Our findings are consistent with the notion that associative learning tends to be more effective when a stimulus or event has uncertainty and thus attracts more attention: Once learning has reached a stable asymptote, no further attention to the stimulus is required, and the associability declines (Pearce & Hall, 1980; Pearce & Bouton, 2001). Neuroimaging work suggests that different neural mechanisms contribute to the early and late stages of visuomotor adaptation, as evidenced by a shift in neural activity from prefrontal to parietal and cerebellar regions (Doyon & Benali, 2005; Doyon & Ungerleider, 2002; Shadmehr & Holcomb, 1997), influencing how these associations are formed.

Although we have shown that the attentional context is associated with visuomotor adaptation for abrupt perturbations that induce large discrepancies between the desired and actual movements (Im et al., 2015, 2016; Song & Bédard, 2015; Wang & Song, 2017; Wang et al., 2022), one remaining question is whether the abrupt perturbation is necessary to promote the association between the attentional context and visuomotor adaptation. Abrupt adaptation is characterized

by extended exposure to large errors, at least immediately after the onset of the perturbation, which induce explicit strategy-based learning by triggering awareness (Taylor et al., 2014). Alternatively, perturbations can be introduced gradually, driven by the accumulation of small errors over time. For example, in many Chinese Kung Fu movies, Shaolin monks start training as young children. To improve their strengths and skills, each trainee is assigned to hug a sapling and try to rip it out of the ground. Each day, the sapling grows steadily larger, and the trainee grows and becomes increasingly stronger while attempting to uproot it. Because of the gradual changes, the trainee remains unaware but continues to improve.

Gradual adaptation tasks that incrementally introduce a perturbation have been suggested to reduce awareness of error signals (e.g., Klassen et al., 2005), which theoretically limits the involvement of explicit cognitive strategies. In this context, adaptation can still be achieved by implicit processes that operate on sensory prediction errors to update internal models (Tseng et al., 2007), even for exceedingly small errors (Hutter and Taylor, 2018; Kim et al., 2018). Previous work indicates that gradual adaptation is distinct from abrupt adaptation (Kluzik et al., 2008; Malfait & Ostry, 2004). Gradual adaptation was suggested to produce more robust aftereffects (Criscimagna-Hemminger et al., 2010; Ingram et al., 2000; Kagerer et al., 1997) and better retention (Huang & Shadmehr, 2009; Klassen et al., 2005). Furthermore, small and large errors may engage different learning processes (Hutter & Taylor, 2018) and rely on distinct neural substrates (Criscimagna-Hemminger et al., 2010).

Given the differences between the learning processes and outcomes of abrupt and gradual adaptation, it is unclear whether the attentional context can serve as an effective contextual cue for recall when the initial adaptation occurs in response to a gradual perturbation. Moreover, it is unknown whether the attentional context cue can be transferred across task types when adapting to a gradual perturbation, as observed for abrupt perturbations (Im et al., 2016; Song & Bédard, 2015; Wang & Song, 2017). The main purposes of this study were to investigate 1) whether an abrupt perturbation is necessary for associating the attentional context and visuomotor adaptation and 2) whether re-learning is impaired when the same attentional context (i.e., divided attention) is maintained between the initial adaptation and recall but the secondary task is different.

In three experiments, a visuomotor rotation task (primary task; Figure 1A) was combined with various attention-demanding tasks (secondary tasks; Figures 1B and 1C). Experiment 1 examined whether attentional context was associated with visuomotor adaptation to a gradual perturbation, which did not produce the same sustained, large errors as the abrupt perturbations employed in our previous work. We found that recall was better when the attentional context was the same (i.e., undivided to undivided or divided to divided) during the initial adaptation and recall compared to when it changed (i.e., divided to undivided), replicating our previous studies that employed an abrupt perturbation (Im et al., 2015, 2016; Song, 2019; Song & Bédard, 2015; Wang & Song, 2017). This suggests that an abrupt perturbation that induces large errors is not necessary for associating the attentional context and visuomotor adaptation. Experiment 2 further showed that

the association between attentional context and visuomotor adaptation occurred not only during the late stage of adaptation, when errors were large and participants were more likely to be aware of the perturbation, but also during the early stage of adaptation, when errors were small and awareness was rare. Finally, Experiment 3 showed that the effect of attentional context on visuomotor adaptation still occurred when different secondary tasks were performed during the initial adaptation and recall but the divided attentional context remained the same.

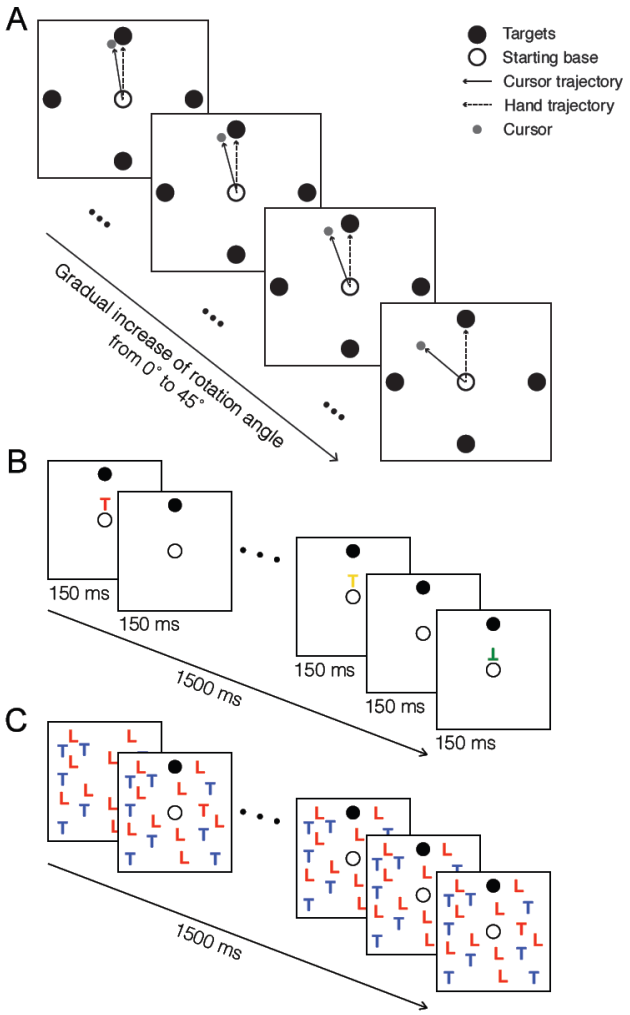


**Figure 1. Task schematics. (A)** Visuomotor rotation task. Targets appeared one at a time and remained visible for the entire trial. During the baseline and washout phases, the cursor followed the hand normally. During the adaptation phase, the cursor position was rotated counterclockwise (CCW) with respect to the hand, from 0 deg to 45deg with an increment of 0.3 deg. During the recall phase, the cursor position was rotated 45 deg CCW relative to the hand for all trials. **(B)** RSVP task. A sequence of five T's was presented, each for 150 ms in either an upright or inverted orientation and one of five different colors. Participants reported how many target T's (upright, red T's and inverted, green T's) were presented via key press at the end of each trial. **(C)** Visual search task. A search array consisting of either an upright or inverted red T and 16 distractors (blue T's and red L's) was presented for 1500 ms. Participants reported whether the red target T was in the upright or inverted orientation via keypress at the end of each trial.

## MATERIALS AND METHODS

### Participants

A total of 175 right-handed undergraduates were recruited for three experiments (Experiment 1: $N$ = 30; Experiment 2: $N$ = 105; Experiment 3: $N$ = 40). See Table 1 for the participant demographics. In Experiments 1 and 3, 10 participants were assigned to each group. In Experiment 2, the group sample sizes were increased to 15 to account for the greater number of pairwise statistical comparisons due to the addition of four experimental groups. These sample sizes are comparable to our previous studies (Bédard & Song, 2013; Im et al., 2015, 2016; Song & Bédard, 2015; Wang & Song, 2017; Wang et al., 2022), which employed a similar dual task paradigm and experimental design and resulted in reliably large effect sizes ($\eta_p^2$ > 0.26). Sample sizes were also comparable to those reported in visuomotor adaptation studies by other groups (e.g., Krakauer et al., 2005; Taylor & Thoroughman, 2007). Eligibility criteria included normal color vision, normal or corrected-to-normal visual acuity, and no prior experience with the visuomotor rotation task. Compensation was provided as course credit. Informed consent was obtained from all participants in accordance with the Declaration of Helsinki, and the experimental procedures were approved by the Institutional Review Board at Brown University.

**Table 1. Participant demographics for Experiments 1-3.** N is the number of participants in each experiment; n is the number of participants per group. Standard deviations are indicated for age.

| | *N* | *n* | Age (years) | Sex (F/M) |
|---|---|---|---|---|
| Experiment 1 | 30 | 10 | 19.2 ± 1.3 | 18 F / 12 M |
| Experiment 2 | 105 | 15 | 19.8 ± 1.2 | 54 F / 51 M |

| | | | | |
|---|---|---|---|---|
| Experiment 3 | 40 | 10 | 19.5 ± 0.9 | 21 F / 19 M |

## Apparatus

Participants sat 57 cm from an Apple iMac computer with a 21-inch monitor (1920 x 1080 pixels; 60 Hz refresh rate) while holding a stylus in their right hand and making keypress responses with their left hand. The stylus tip rested on a digitizing tablet (Magic Touch; Tyco Touch, Inc.) placed horizontally on a table and aligned with the participant's midline and the center of the monitor. Feedback of the hand position was provided by displaying a cursor on the monitor (white dot; 0.25 deg diameter). Visual feedback of the arms was occluded by a solid black surface mounted horizontally at the same height as the bottom of the monitor. MATLAB (R2015a; The MathWorks, Inc.) and Psychtoolbox-3 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997) were used to present visual stimuli and record hand movements.

## Experimental design

### Primary task

**Visuomotor rotation:** Participants were asked to hold a stylus with their right hand and move the cursor from a starting position (yellow annulus; 1 deg diameter) located in the center of the screen to a target (white circle; 1deg diameter) separated by 5.5 cm (Figure 1A). The cursor and target remained visible for the entire 1500 ms trial duration. Participants were instructed to make a rapid, straight-line movement that sliced through the target and then reverse the movement to

return to the starting position. Participants were also encouraged to overshoot the target and avoid making corrective movements.

There were three types of trials. In no rotation trials, the cursor and hand position were the same such that the cursor movement shown on the display corresponded to the participant's hand movement. In gradual rotation trials, the cursor position was rotated counterclockwise (CCW) relative to the hand and gradually increased from 0 deg to 45 deg in increments of 0.3 deg. Each angle was presented once, except for 45 deg, which was repeated for the last 10 trials. Without any corrective movements, the gradual rotation would give the impression that the cursor was slowly diverging from the target direction. In abrupt rotation trials, the cursor position was rotated 45 deg CCW relative to the hand.

The target appeared at one of four potential locations at 3, 6, 9, and 12 o'clock relative to the starting position. Each target location was presented in a pseudorandomized order within blocks of four trials. After 40 practice trials with no cursor rotation, there were four experimental phases: baseline (40 no rotation trials), adaptation (160 gradual rotation trials), washout (80 no rotation trials), and recall (80 abrupt rotation trials). Each experimental phase was completed without breaks.

## Secondary tasks

**Rapid serial visual presentation (RSVP) task (Figure 1B)**: A sequence of five upright or inverted T's was presented in different colors: red, yellow, blue, white, or green. Each T was presented for 150 ms, followed by a 150 ms blank interval. The

T's were always positioned immediately above the starting position. Two types of targets were defined by multiple features: an upright red T and an inverted green T. Participants reported how many targets were presented—either one, two, or three—via keypress at the end of the trial. Even when participants were not asked to perform the secondary task, they made a keypress in response to a prompt (e.g., "Press button 1") to preserve the sequence of actions performed in each trial. To maintain consistent exposure to the visual stimuli across experimental conditions, the RSVP stimuli were presented even if the person was not performing the secondary task. This ensured that changes to the attentional context were not confounded with the (in)consistency of low-level visual stimuli.

**Visual conjunction search task (Figure 1C):** One target (a red T) and 16 distractors (blue T's and red L's, both upright and inverted) were simultaneously presented in pseudorandom positions for the entire trial duration (1500 ms). The target was presented in either an upright or inverted orientation. Participants were asked to report the orientation of the target via keypress. Like in the RSVP task, the search array was displayed even when the participant was not performing the secondary task, and a prompted keypress response was recorded after each trial.

## Procedure

In the three experiments, participants performed the visuomotor rotation task throughout all experimental phases: the baseline with no cursor rotation, the adaptation phase with the gradual cursor rotation with or without the secondary task, the washout phase with no cursor rotation, followed by the recall phase with

the abrupt cursor rotation with or without the secondary task (Tables 2-4). The group assignments are described below for each experiment. In all experiments, task instructions for the secondary task were presented at the beginning of each phase, leading to a short break (30-45 s). When performing the dual task, participants were instructed to initiate a movement as soon as the target was presented while simultaneously paying attention to the visual stimuli to identify either the number of targets presented (RSVP) or the orientation of the targets (visual conjunction search). This ensured that attention was divided among the tasks, allowing us to examine the effect of attentional context on visuomotor adaptation.

**Experiment 1:** Participants were randomly assigned to one of three groups: none-none, rsvp-rsvp, and rsvp-none, named according to the secondary task performed during the adaptation and recall phases, respectively. Depending on which experimental group they were assigned to, some participants performed visuomotor adaptation and secondary tasks at the same time. The none-none and rsvp-rsvp groups performed the visuomotor rotation task under consistent attentional contexts between adaptation and recall (i.e., undivided-undivided for the none-none group and divided-divided for the rsvp-rsvp group). The rsvp-none group performed the visuomotor rotation task under inconsistent attentional contexts (i.e., divided-undivided). Table 2 summarizes the visuomotor adaptation conditions and secondary tasks that each group performed in Experiment 1.

**Table 2. Experiment 1 task details.** Participants performed the primary visuomotor rotation task and secondary RSVP task depending on group assignment.

| | Group | Baseline (40 trials) | Adaptation (160 trials) | Washout (80 trials) | Recall (80 trials) |
|---|---|---|---|---|---|
| Primary task | all | no rotation (0 deg) | gradual rotation (0.3 deg/trial) | no rotation (0 deg) | abrupt rotation (45 deg) |
| Secondary task | none-none | | | | |
| | rsvp-rsvp | rsvp | rsvp | | rsvp |
| | rsvp-none | rsvp | rsvp | | |

**Experiment 2:** We manipulated when the dual task condition was performed during the adaptation phase to examine whether the attentional context was associated with visuomotor memory only after errors had become large (Table 3). Four new groups were formed based on whether participants performed the RSVP task during the early (the first 80 trials) or late (the last 80 trials) phase of adaptation (early vs. late) and whether they performed the RSVP task during the entire 80 trial recall phase (none vs. rsvp).

For example, the early rsvp-rsvp group performed the RSVP task during the early phase (first 80 trials) of adaptation and the recall phase. By contrast, the late rsvp-none group performed the RSVP task during the late phase (last 80 trials) of adaptation, but did not perform a secondary task during the recall phase. For data analyses, we combined the early rsvp-rsvp and late rsvp-none groups and classified them as the *early-adaptation consistent* group because the attentional context at recall was the same as the early phase of adaptation in this group (divided and undivided, respectively). Conversely, we combined the late rsvp-rsvp and early rsvp-none groups and classified them as the *late-adaptation consistent* group

because the attentional context at recall was the same as the late phase of adaptation in this group (again, divided and undivided, respectively).

We also formed the same three groups from Experiment 1, which performed either a single or dual task during the entire adaptation phase (none-none, rsvp-rsvp, and rsvp-none; Table 3). This allowed us to confirm the results of Experiment 1 and evaluate whether the attentional context was associated with visuomotor adaptation during the early or late phase of adaptation (80 trials) in comparison to the entire adaptation phase (160 trials).

Finally, we questioned participants about their subjective awareness of the cursor perturbation using a brief exit survey immediately following the experimental session. The question provided to the participants was: *"You completed five blocks of trials where you performed a reaching task under different conditions. During the experiment, did you notice any systematic changes to the relationship between your hand movement and the cursor movement? If so, please describe the changes and when you became aware of them. You can refer to blocks 1-5 to indicate the timing."* This survey provided a coarse-grained measure of when participants noticed that the cursor movements had been manipulated. After a response was obtained, participants were debriefed about the experiment.

**Table 3. Experiment 2 task details.** Participants performed the primary visuomotor rotation task and secondary RSVP task depending on group assignment.

| | Group | Baseline (40 trials) | Early adaptation (80 trials) | Late adaptation (80 trials) | Washout (80 trials) | Recall (80 trials) |
|---|---|---|---|---|---|---|
| Primary task | all | no rotation (0 deg) | gradual rotation (0.3 deg/trial) | gradual rotation (0.3 deg/trial) | no rotation (0 deg) | abrupt rotation (45 deg) |
| Secondary task | early rsvp-rsvp | rsvp | rsvp | | | rsvp |

| | | | | | |
|---|---|---|---|---|---|
| Early-adaptation consistent | late rsvp-none | rsvp | | rsvp | |
| Late-adaptation consistent | late rsvp-rsvp | rsvp | | rsvp | rsvp |
| | early rsvp-none | rsvp | rsvp | | |
| Replicate | none-none | | | | |
| | rsvp-rsvp | rsvp | rsvp | rsvp | rsvp |
| | rsvp-none | rsvp | rsvp | rsvp | |

**Experiment 3:** We replaced the secondary RSVP task with a visual conjunction search task (Figure 1C) with three comparable group assignments to Experiment 1: none-none, search-search, and search-none. To assess the generalizability of the effect of attentional context, we also included a new group that performed the visual search task during adaptation and the RSVP task during recall. Participants were randomly assigned to one of the four groups: none-none, search-search, search-none, and search-rsvp (Table 4). The none-none and search-search groups had consistent attentional contexts between adaptation and recall, while the search-none group had an inconsistent attentional context. The search-rsvp group was considered to have a consistent attentional context with respect to the dual task conditions (i.e., divided attention) but engaged in either a spatial (conjunction search) or temporal (RSVP) attention task. The addition of this group allowed us to examine whether attentional context encoded under gradual adaptation could be transferred across tasks that engaged different types of attention.

**Table 4. Experiment 3 task details.** Participants performed the primary visuomotor rotation task and secondary visual search task or RSVP task depending on group assignment.

| | Group | Baseline (40 trials) | Adaptation (160 trials) | Washout (80 trials) | Recall (80 trials) |
|---|---|---|---|---|---|
| Primary task | all | no rotation (0 deg) | gradual rotation (0.3 deg/trial) | no rotation (0 deg) | abrupt rotation (45 deg) |

| | | | | |
|---|---|---|---|---|
| Secondary task | none-none | | | |
| | search-search | search | search | search |
| | search-none | search | search | |
| | search-rsvp | search | search | rsvp |

## Data analyses

Data analyses were performed in MATLAB R2021b and were the same across Experiments 1-3. Movement analyses were restricted to the center-out movement to the target. Hand position coordinates were filtered using a 2nd-order, low-pass Butterworth filter with a 6 Hz cutoff, which was determined through residual analysis. Hand position data were transformed to a common reference frame with the target located at the 12 o'clock position. Hand displacements were obtained using a first-order backward difference. Net hand displacements were computed as the square root of the sum of the squared x- and y-displacements. Hand tangential velocity was obtained by dividing the net hand displacements by the sampling interval (1/200 Hz = .005 s). Movement onset and offset were identified when the hand tangential velocity first exceeded and fell below 5% of peak velocity. Each movement trajectory and velocity profile were visually inspected to ensure that the entire movement was captured by the movement detection algorithms.

Hand angle—the angular difference between the target and the initial movement direction—was used to measure performance on the visuomotor rotation task. The initial movement direction was defined as the line connecting the hand position at movement onset and peak velocity each trial. A positive hand angle denoted clockwise deviations relative to the target, while a negative hand angle

denoted CCW deviations. Trials were excluded if the hand angle exceeded ± 90°, indicating a movement in the wrong direction, or deviated more than 25 deg from the median of the five previous and successive trials. This criterion led to the retention of more trials than ± 5 local median absolute deviations as a threshold. The total number of trials removed were: 180 (2.75%) of 10,800 trials in Experiment 1, 460 (1.22%) of 37,800 trials in Experiment 2, and 298 (1.67%) of 14,400 trials in Experiment 3. Adjusting the outlier removal parameters within reasonable limits did not affect the reported results. Hand angle was then averaged across blocks of four successive trials, one per target location, the same as our previous work (e.g., Im et al., 2015; 2016; Song & Bédard, 2013; 2015). RSVP and visual search performance were assessed as the proportion of correct responses (i.e., accuracy) within each experimental phase.

**Statistical analyses**

Statistical analyses for Experiments 1-3 were performed using SAS 9.4. Hand angle was compared across groups within each of the experimental phases using two-way mixed model ANOVAs with Group (between-subjects) and Block (within-subjects) as fixed factors and participant as a random factor. Summary measures of hand angle computed across different time windows were compared using one-way ANOVAs with Group (between-subjects) as a fixed factor. Secondary task accuracy scores were compared to chance level performance using two-sided *t*-tests. Chance performance was 0.33 for the RSVP task and 0.5 for the visual conjunction search task. Accuracy scores were also compared using two-way mixed model ANOVAs

with Group (between-participants) and Phase (within-participants) as fixed factors and participant as a random factor. One-way ANOVAs were employed to compare accuracy within a group across experimental phases. Statistical significance was assessed at the $a$ = .05 level. Bonferroni corrections were applied for multiple post-hoc comparisons (i.e., unplanned contrasts). Partial eta squared was computed as a measure of effect size for main effects and interactions.

For Experiment 2, the RSVP accuracy and hand angle of the early rsvp-rsvp and late rsvp-none groups were merged to form the early-adaptation consistent group. Likewise, the RSVP accuracy and hand angle of the late rsvp-rsvp and early rsvp-none groups were merged to form the late-adaptation consistent group. This allowed us to address our main question of whether the differences in the error magnitudes between the early and late stages of adaptation influenced when the attentional context was encoded. Note that participants in the early-adaptation consistent group experienced a consistent attentional context between recall and the early half of the adaptation phase, which was characterized by relatively small errors. By contrast, participants in the late-adaptation consistent group experienced a consistent attentional context between recall and the late half of the adaptation phase, which was characterized by relatively large errors. Prior to the statistical analyses, we confirmed no differences in the RSVP or the hand angle results between the two early-adaptation consistent groups or between the two late-adaptation consistent groups. Detailed comparisons between the early rsvp-rsvp and late rsvp-none groups (Figure S1) and between the late rsvp-rsvp and early rsvp-none groups (Figure S2) were included as Supplemental Data.

## RESULTS

We first present the effects of visuomotor adaptation on the secondary task and vice versa that were commonly observed across the three experiments. We then address the impact of the (in)consistency of attentional context on visuomotor memory recall for each experiment separately.

### Experiments 1, 2, and 3: Common Results

#### No effect of visuomotor adaptation on the secondary task performance

There was no systematic difference in the secondary task performance across groups or experimental phases, confirming that visuomotor adaptation did not interfere with the secondary task performance in Experiments 1-3. Figure 2A shows the mean proportion of correct responses during the baseline, adaptation, and recall phases for the groups that performed the RSVP task in Experiment 1. Both the rsvp-rsvp (blue) and rsvp-none (red) groups performed better than the chance level of 0.33 (dashed line; all *p's* < 0.01), indicating that attention was allocated to the secondary task. The chance level for the RSVP task was 0.33 because participants were asked to report whether one, two, or three targets (upright red or inverted green T's) were presented in the RSVP stream. Group performance was not different during baseline or adaptation as confirmed by a two-way mixed-model ANOVA with Group (rsvp-rsvp, rsvp-none) and Phase (baseline, adaptation) as fixed factors and participant as a random factor (Group: $F_{1,18} = 0.00$, $p = 0.96$, $\eta_p^2 = 0.00$; Phase: $F_{1,18} = 4.05$, $p = 0.06$, $\eta_p^2 = 0.09$; Group x Phase: $F_{1,18} = 3.24$, $p = 0.09$, $\eta_p^2 = 0.08$). A separate

one-way ANOVA confirmed that RSVP performance did not differ across the baseline, adaptation, and recall phases within the rsvp-rsvp group ($F_{2,18}$ = 2.16, $p$ = 0.14, $\eta_p^2$ = 0.13).

Figure 3A shows the RSVP accuracy for the rsvp-rsvp (blue), rsvp-none (red), early-adaptation consistent (orange), and late-adaptation consistent (purple) groups in Experiment 2. Note that the participants in the late rsvp-none condition (early-adaptation consistent group) and the early rsvp-none condition (late-adaptation consistent group) performed the secondary RSVP task during the half of adaptation but not during recall. Thus, the ANOVA to compare RSVP accuracy during recall excluded the data from these groups. All four groups performed the RSVP task better than the 0.33 chance level (all $p$'s < 0.01). We found no differences in the RSVP performance during baseline or adaptation: a two-way mixed model ANOVA with Group (rsvp-rsvp, rsvp-none, early-adaptation consistent, late-adaptation consistent) and Phase (baseline, adaptation) indicated no main effect of Group ($F_{3,86}$ = 0.59, $p$ = 0.62, $\eta_p^2$ = 0.01) or Phase ($F_{1,86}$ = 0.53, $p$ = 0.47, $\eta_p^2$ = 0.00) and no interaction ($F_{3,86}$ = 0.48, $p$ = 0.70, $\eta_p^2$ = 0.01). We also conducted a separate two-way ANOVA with Group (rsvp-rsvp, early-adaptation consistent, late-adaptation consistent) and Phase (baseline, adaptation, and recall) to examine the RSVP accuracy of the participants who performed the RSVP task during the recall phase. We found no significant main effects of Group ($F_{2,42}$ = 0.31, $p$ = 0.74, $\eta_p^2$ = 0.00) or Phase ($F_{2,84}$ = 0.70, $p$ = 0.50, $\eta_p^2$ = 0.01), but a significant Group x Phase interaction ($F_{4,84}$ = 2.94, $p$ = 0.03, $\eta_p^2$ = 0.08). Post-hoc comparisons revealed only that accuracy

decreased between the adaptation and recall phases in the rsvp-rsvp group (5.8%, $t_{84}$ = 2.06, $p$=0.04). There were no other differences within or between groups.

Figure 4A shows the visual search and RSVP accuracy in Experiment 3. Visual search and RSVP accuracy were above chance levels in all groups (all $p$'s < 0.01). Note that chance performance in the visual search task was 0.5 because participants reported whether the target (a red T) was in either an upright or inverted orientation. Visual search accuracy was first compared among the search-search, search-none, and search-rsvp groups using a two-way mixed model ANOVA with Group and Phase (baseline, adaptation) as fixed factors and participant as a random factor, which revealed no significant effects (Group: $F_{2,27}$ = 2.38, $p$ = 0.11, $\eta_p^2$ = 0.08; Phase: $F_{1,27}$ = 1.95, $p$ = 0.17, $\eta_p^2$ = 0.03; Group x Phase: $F_{2,27}$ = 2.03, $p$ = 0.15, $\eta_p^2$ = 0.07). This indicated that visual search accuracy did not differ throughout baseline and adaptation. Subsequently, we compared the search-search and search-rsvp groups during baseline, adaptation, and recall. The two-way mixed model ANOVA with Group and Phase as fixed factors and participant as a random factor again revealed no significant effects (Group: $F_{1,18}$ = 2.29, $p$ = 0.15, $\eta_p^2$ = 0.04; Phase: $F_{2,36}$ = 2.62, $p$ = 0.09, $\eta_p^2$ = 0.08; Group x Phase: $F_{2,36}$ = 0.63, $p$ = 0.54, $\eta_p^2$ = 0.02). Together, these results replicate our past work (Bédard & Song, 2013; Im, Bédard, & Song, 2015; Song & Bédard, 2015; Wang & Song, 2017), showing that visuomotor adaptation did not impact the secondary task performance.

**No effect of the secondary task on the primary visuomotor rotation task performance**

In our previous studies with an abrupt perturbation, we demonstrated that the secondary task did not interfere with visuomotor adaptation (Bédard & Song, 2013; Im et al., 2015; 2016; Song & Bédard, 2015 Wang & Song, 2017). Here we replicated the results by confirming that there was no systematic difference in the hand angle data across groups or experimental phases. In the three experiments (shown in Figures 2B, 3B, and 4B for Experiments 1, 2, and 3, respectively), we observed that participants initially made accurate reaches directed toward the target with no differences among the groups during the baseline phase (Blocks 1-10). During the adaptation phase, the hand angle increased over successive blocks (~0.2 deg/trial), partially compensating for the increasing rotation (0.3 deg/trial). The rate and degree of adaptation were compared among the groups within each experiment, and no differences were found, as shown by the overlapping hand angle curves (Blocks 11-50). During washout, the hand angle decreased following the removal of the rotation, returning to near baseline levels (~3 deg) in all groups Blocks 71-90). To confirm these observations, hand angle was examined using two-way mixed model ANOVAs with Group (between-subjects) and Block (within-subjects) as fixed factors and participant as a random factor during the baseline, adaptation, and washout phases. Statistical analyses were conducted separately for each experiment.

In Experiment 1, we compared hand angle among the none-none (black), and rsvp-rsvp (blue), and rsvp-none (red) groups (Figure 2B). In the baseline phase, there were no group differences: the main effect of Group ($F_{2,27} = 0.35$, $p = 0.71$, $\eta_p^2 = 0.00$) and Group x Block interaction ($F_{18,243} = 0.84$, $p = 0.65$, $\eta_p^2 = 0.06$) were not

significant. However, there was a main effect of Block ($F_{9,243}$ = 2.04, $p$ = 0.04, $\eta_p^2$ = 0.05). Post-hoc comparisons revealed that the last block was slightly lower than others (Blocks 2-6 and 9) with mean differences ranging from 1.4 - 2.1 deg. In the adaptation phase, the main effect of Group ($F_{2,27}$ = 0.34, $p$ = 0.71, $\eta_p^2$ =0.00) and the Group x Block interaction ($F_{78,1053}$ = 0.44, $p$ = 0.99, $\eta^2$ =0.03) were not significant. However, there was an expected main effect of Block ($F_{39,1053}$ = 227.96, $p$ < 0.01, $\eta_p^2$ = 0.88), indicating that hand angle increased to counteract the gradual cursor rotation. To ensure that adaptation was at comparable levels by the end of the adaptation phase, we also compared the mean hand angle over the last five blocks (20 trials). A one-way ANOVA indicated that the degree of adaptation did not differ among the groups ($F_{2,27}$ = 0.02, $p$ = 0.98, $\eta_p^2$ = 0.00). Thus, adaptation outcomes were comparable among the groups despite differences in attentional demands (none-none vs. rsvp-rsvp and rsvp-none). In the washout phase, there was a significant main effect of Group ($F_{2,27}$ = 3.60, $p$ = 0.04, $\eta_p^2$ = 0.01). Post-hoc comparisons indicated elevated hand angle in the rsvp-none group compared to the none-none (1.37 deg, $t_{27}$ = 2.25, $p$ = 0.03) and rsvp-rsvp groups (1.46 deg, $t_{27}$ = 2.39, $p$ = 0.02). The main effect of Block ($F_{19,513}$ = 51.84, $p$ < 0.01, $\eta_p^2$ = 0.63) was also significant, indicating that hand angle gradually decreased after the cursor rotation was removed, whereas the Group x Block interaction was not significant ($F_{38,513}$ = 1.27, $p$ = 0.13, $\eta_p^2$ = 0.08).

In Experiment 2, we compared hand angle among the none-none (black), rsvp-rsvp (blue), rsvp-none (red), early-adaptation consistent (orange), and late-adaptation consistent (purple) groups (Figure 3B). In the baseline phase, there were

no group differences: the main effect of Group ($F_{4,100}$ = 0.60, $p$ = 0.66, $\eta_p^2$ = 0.00) and Group x Block interaction ($F_{36,900}$ = 1.07, $p$ = 0.35, $\eta_p^2$ = 0.02) were not significant. However, there was a main effect of Block ($F_{9,900}$ = 2.83, $p$ < 0.01, $\eta_p^2$ = 0.04). Post-hoc comparisons revealed no discernable pattern—i.e., no single block or set of blocks that was consistently different from others. The largest difference was 1.0 deg and none of the pairwise comparisons were significant following adjustment. In the adaptation phase, the main effect of Group ($F_{4,100}$ = 1.54, $p$ = 0.20, $\eta_p^2$ =0.00) and the Group x Block interaction ($F_{156,3900}$ = 0.95, $p$ = 0.65, $\eta_p^2$ =0.93) were not significant, indicating no group differences. The main effect of Block ($F_{39,3900}$ = 1430.04, $p$ < 0.01, $\eta_p^2$ = 0.04) indicated steady increases to hand angle to counteract the cursor rotation. The mean hand angle at the last five blocks (20 trials) of the adaptation phase was compared across the groups. A one-way ANOVA indicated that the degree of adaptation did not differ among the groups ($F_{4,100}$ = 0.92, $p$ = 0.46, $\eta_p^2$ = 0.04). In the washout phase, there were no group differences: the main effect of Group ($F_{4,100}$ = 1.86, $p$ = 0.12, $\eta_p^2$ = 0.00) and the Group x Block interaction ($F_{76,1900}$ = 0.82, $p$ = 0.87, $\eta_p^2$ = 0.03) were not significant. The main effect of Block was significant ($F_{19,1900}$ = 329.81, $p$ < 0.01, $\eta_p^2$ = 0.75), indicating that hand angle decreased after the rotation was removed.

In Experiment 3, we compared hand angle among the none-none (black), search-search (blue), search-none (red), and search-rsvp (green) groups (Figure 4B). In the baseline phase, there were no significant differences: the main effects of Group ($F_{3,36}$ = 1.33, $p$ = 0.28, $\eta_p^2$ = 0.01) and Block ($F_{9,324}$ = 1.38, $p$ = 0.20, $\eta_p^2$ = 0.03)

were not significant, nor was the interaction ($F_{27,324}$ = 0.86, $p$ = 0.67, $\eta_p^2$ = 0.06). In the adaptation phase, neither the main effect of Group ($F_{3,36}$ = 0.16, $p$ = 0.93, $\eta_p^2$ =0.00) nor the Group x Block interaction ($F_{117,1404}$ = 0.86, $p$ = 0.85, $\eta_p^2$ =0.06) were significant. The main effect of Block, however, was significant ($F_{39,1404}$ = 230.28, $p$ < 0.01, $\eta_p^2$ = 0.85), reflecting gradually increasing hand angle to counteract the cursor rotation, as expected. The mean hand angle in the final five adaptation blocks (20 trials) was compared using a one-way ANOVA, which indicated that the degree of adaptation did not differ among the groups ($F_{3,36}$ = 0.24, $p$ = 0.86, $\eta_p^2$ = 0.02). These analyses indicate that there were no differences in how the groups adapted to the gradual visuomotor rotation, replicating the results reported in Experiments 1 and 2. In the washout phase, there were no group differences: The main effect of Group ($F_{3,36}$ = 0.30, $p$ = 0.82, $\eta_p^2$ = 0.00) and the Group x Block interaction ($F_{57,684}$ = 0.55, $p$ = 0.99, $\eta_p^2$ = 0.04) were not significant. The main effect of Block was significant ($F_{19,684}$ = 48.13, $p$ < 0.01, $\eta^2$ = 0.54), indicating the decreasing hand angle following the removal of the rotation, also as expected.

Together, the statistical analyses confirm no group differences in visuomotor adaptation through the baseline, adaptation, and washout phases in Experiments 1-3. Note that some groups (e.g., the rsvp-rsvp and rsvp-none groups in Experiments 1 and 2 and the search-search, search-none, and search-rsvp groups in Experiment 3) performed the secondary task during adaptation, but the none-none groups did not. Despite the differences in attentional demands, the lack of group differences reported above suggests that the secondary task did not interfere with visuomotor adaptation to a gradual perturbation, which is consistent with our previous studies

that employed an abrupt perturbation (Bédard & Song, 2013; Im et al., 2015; 2016; Song & Bédard, 2015 Wang & Song, 2017). This also rules out the possibility that group differences observed during recall resulted different adaptation responses.

## Experiment 1

### Impaired re-learning in a single task context when the initial adaptation occurred in a dual task context

Experiment 1 examined whether changes to attentional context would impair the recall of visuomotor adaptation to a gradual perturbation. If recall was impaired when changing from the dual task to single task condition (rsvp-none group), this would suggest that the attentional context was associated with visuomotor adaptation even when participants were minimally aware of the perturbation. Indeed, this was what we observed: we observed a worse recall performance in the rsvp-none group compared to the none-none and rsvp-rsvp groups who maintained the same single- or dual-task conditions across learning and recall.

During the recall phase, an abrupt 45 deg CCW rotation was consistently applied each trial (Blocks 71-90). The none-none and rsvp-rsvp groups showed comparable increases in hand angle, suggesting similar recall performance (Figure 2B; black and blue curves). However, the rsvp-none group showed slower re-learning than the other two groups (Figure 2B; red curve). Hand angle was compared using a two-way mixed-model ANOVA with Group (none-none, rsvp-rsvp, and rsvp-none) and Block as fixed factors and participant as a random factor. The main effect of Block was significant ($F_{19,513}$ = 39.05, $p$ < 0.01, $\eta_p^2$ =0.56), while the

main effect of Group was not ($F_{2,27}$ = 2.48, $p$ = 0.10, $\eta_p^2$ =0.01). However, the Group x Block interaction ($F_{38,513}$ = 2.18, $p$ < 0.01, $\eta_p^2$ =0.13) was significant. Post-hoc comparisons indicated decreased hand angle in the rsvp-none group during the early stages of recall.

We computed the mean hand angle over five blocks from 73-77 (20 trials) during the early stage of recall (Figure 2C) and compared among the groups with a one-way ANOVA, which indicated significant group differences ($F_{2,27}$ = 8.12, $p$ < 0.01, $\eta_p^2$ = 0.37). Post-hoc comparisons during early recall indicated lower hand angle in the rsvp-none group compared to the none-none (5.0 deg, $t_{27}$ = 2.44, $p$ = 0.02) and rsvp-rsvp groups (8.3 deg, $t_{27}$ = 4.00, $p$ < .01). There was no difference between the none-none and rsvp-rsvp group (3.2 deg, $t_{27}$ = 1.56, $p$ = 0.13). This suggests that recall was impaired in the rsvp-none group, who experienced inconsistent attentional contexts between adaptation (divided attention) and recall (undivided attention), compared to the none-none and rsvp-rsvp groups, who experienced consistent attentional contexts between adaptation and recall.

Experiment 1 showed that the recall of visuomotor adaptation acquired under a gradual adaptation was impaired by changes to the attentional context between adaptation and recall (rsvp-none group), compared to when the attentional context remained the same (none-none and rsvp-rsvp groups). This is in line with our previous reports of impaired recall under a different attentional context following exposure to an abrupt 45 deg rotation (Im et al., 2015, 2016; Song & Bédard, 2015; Wang & Song, 2017; Wang et al., 2022). Furthermore, the small errors

observed in Experiment 1 suggest that explicit awareness of the perturbation may not be necessary for encoding the attentional context.

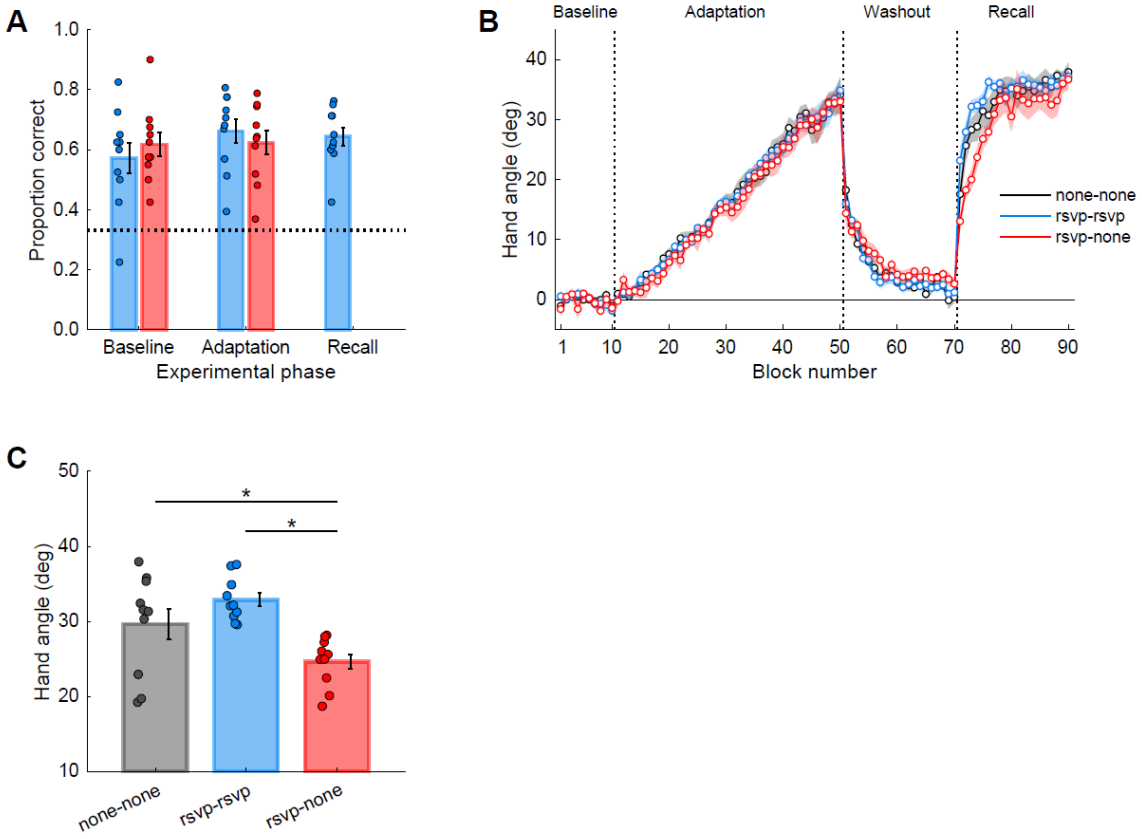


**Figure 2. Experiment 1 results. (A)** RSVP accuracy for the rsvp-rsvp (blue) and rsvp-none (red) groups during the baseline, adaptation, and recall phases. Both groups performed above the chance level (0.33; dotted line). The error bars indicate the standard error of the mean (SEM). **(B)** Hand angle for the none-none (black), rsvp-rsvp (blue), and rsvp-none (red) groups during each block of the baseline, adaptation, washout, and recall phases. Shaded areas indicate the SEM. **(C)** Mean hand angle for recall blocks 3-7 (20 trials). The error bars indicate the SEM. The asterisks indicate significant group differences at the $p < 0.05$ level. See text for additional details.

## Experiment 2

### Error magnitude did not impact the association of attentional context and visuomotor adaptation

Experiment 1 found that recall performance was impaired in the rsvp-none group compared to the other groups despite comparable performance among the three

groups during the initial adaptation phase. This suggests impaired re-learning following the change to attentional context is not due to differences in explicit awareness across the groups. However, Experiment 1 does not rule out the possibility that association of attentional context and visuomotor adaptation occurred towards the end of adaptation, when motor errors were large enough to be perceived (~10 deg).

Thus, Experiment 2 examined whether the magnitude of the error signals was crucial for associating the attentional context with visuomotor adaptation. If so, recall performance should be enhanced in participants who experience the same attentional context during the late stage of adaptation and recall, but not during the early stage of adaptation and recall. In Experiment 1, errors continuously accumulated because the rate of adaptation (0.2 deg/trial) tended to be slower than the rate of the perturbation (0.3 deg/trial). If the emergence of perceivable errors is not necessary for associating the attentional context and visuomotor adaptation, recall performance should not be impacted by whether the attentional context experienced during the early stage of adaptation is reinstated at recall. To address this, we directly compared the early- and late-adaptation consistent groups to examine whether the early-adaptation consistent group who was less likely to be aware of the gradual perturbation would show impaired recall, relative to the late-adaptation consistent group. If this were the case, it would suggest that attentional context was more likely to be linked to explicit awareness processes. Alternatively, if the two groups showed comparable recall performance regardless of whether error signals were small (early) or large (late), this would suggest that the encoding

of attentional context was independent of error signal magnitude and explicit awareness. What we observed was consistent with the latter: the recall performance in the early-adaptation consistent group was comparable to that in the late-adaptation consistent group.

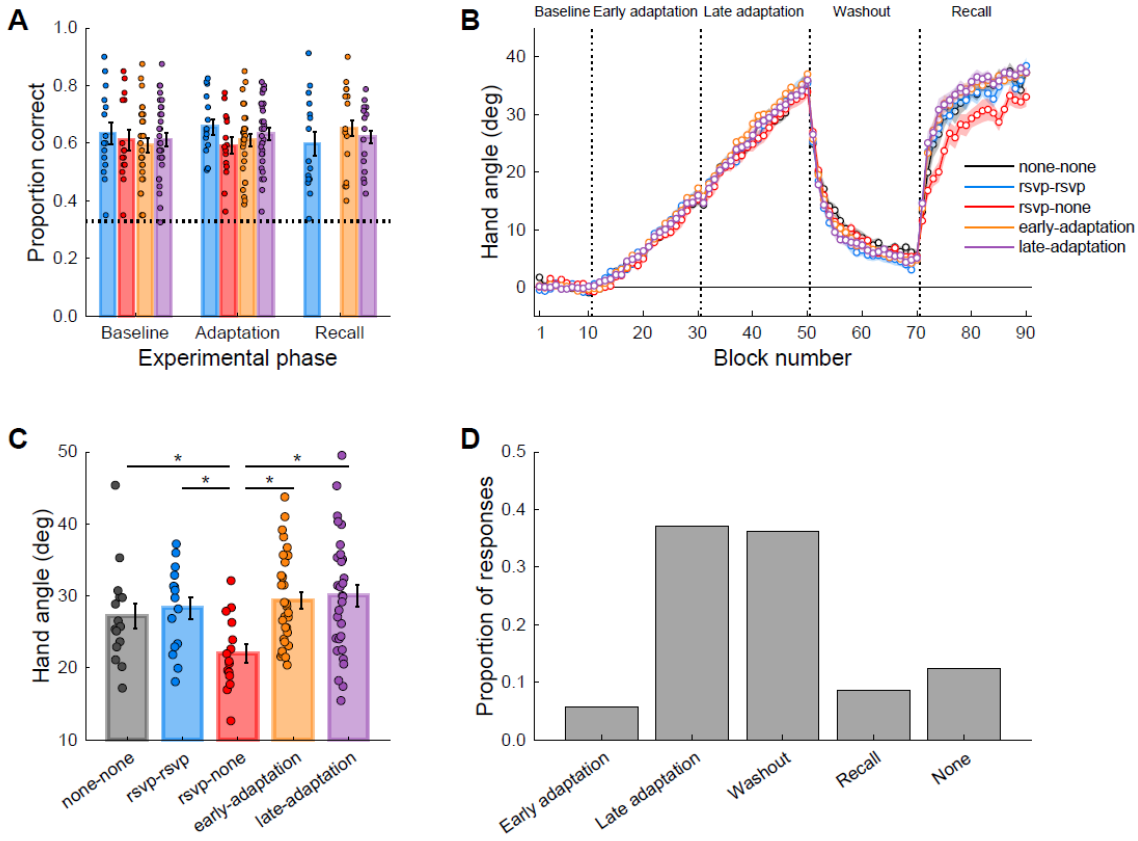


**Figure 3. Experiment 2 results. (A)** RSVP accuracy in the rsvp-rsvp (blue), rsvp-none (red), early-adaptation consistent (orange), and late-adaptation consistent (purple) groups during the baseline, adaptation, and recall phases. All groups performed above the chance level (0.33; dotted line). The error bars indicate the standard error of the mean (SEM). **(B)** Hand angle for the none-none (black), rsvp-rsvp (blue), rsvp-none (red), early-adaptation consistent (orange), and late-adaptation consistent (purple) groups during each block of the baseline, adaptation, washout, and recall phases. Shaded areas indicate the SEM. **(C)** Mean hand angle for recall blocks 3-7 (20 trials). The error bars indicate the SEM. The asterisks indicate significant group differences at the $p < 0.05$ level. **(D)** Proportion of participants that reported being aware of the pertubration within each experimental phase. See text for additional details.

As shown in Figure 3B, we observed substantial overlap in the hand angle between the early- and late-adaptation consistent groups during recall. A two-way mixed-model ANOVA comparing hand angle during the recall phase with Group (early-adaptation consistent and late-adaptation consistent) and Block (20 recall blocks) showed a significant main effect of Block ($F_{19,1102}$ = 150.13, $p$ < 0.01, $\eta_p^2$ = 0.71), indicating that re-adaptation occurred to counteract the 45 deg cursor perturbation, as expected. More importantly, neither the main effect of Group ($F_{1,58}$ = 0.05, $p$ = 0.82, $\eta_p^2$ = 0.00) nor the Group x Block interaction ($F_{19,1102}$ = 0.57, $p$ =0.93, $\eta_p^2$= 0.01) was significant. We also compared the mean hand angle, averaged across the recall blocks 3-7 (20 trials), and found no significant differences (Figure 3C; $F_{1,58}$ = 0.11, $p$ = 0.74, $\eta_p^2$ = 0.00).

The lack of differences between the early- and late- adaptation consistent groups suggested that the error magnitude was not a critical factor. However, because both groups performed the secondary RSVP task on only half of the adaptation trials compared to the none-none, rsvp-rsvp, and rsvp-none groups in Experiment 1, the association of attentional context and visuomotor adaptation may have been weakened in the early- and late-adaptation consistent groups due to the limited exposure to either attentional context.

Therefore, we compared the recall performance of the early- and late-adaptation consistent groups with that of the three groups replicated from Experiment 1: none-none, rsvp-rsvp, and rsvp-none. If the recall performance of the early- and late-adaptation consistent groups were comparable to that of the none-none and rsvp-rsvp groups, this would suggest that neither the early- nor late-

adaptation consistent groups showed impairment. On the other hand, if the recall of the early- and late-adaptation consistent groups were comparable to that of the rsvp-none group, this would suggest that neither attentional context was associated with visuomotor adaptation, leading to the impaired recall.

First, we confirmed that the recall performance of the none-none, rsvp-rsvp, and rsvp-none groups in Experiment 2 replicated the pattern observed, with different participants, in Experiment 1. As shown in Figure 3B (black, blue, and red curves), the two consistent attentional context groups (none-none and rsvp-rsvp) showed hand angle increasing at the same rate and to the same degree throughout the recall phase, while the inconsistent attentional context group (rsvp-none) showed reduced adaptation. This observation was confirmed by a significant main effect of Group ($F_{2,42}$ = 4.82, $p$ = 0.01, $\eta_p^2$ = 0.01), indicating impaired re-learning in the rsvp-none group compared to the none-none and rsvp-rsvp groups (both $p$'s < 0.05). This was further supported by reduced mean hand angles during recall blocks 3-7 (20 trials) in the rsvp-none group, compared to the none-none and rsvp-rsvp groups (both $p$'s < 0.05). Thus, Experiment 2 replicated the results of Experiment 1, namely the reduced recall performance in the rsvp-none group compared to the none-none and rsvp-rsvp groups.

We next compared the performance of the early- and late-adaptation consistent groups to the other groups (none-none, rsvp-rsvp, and rsvp-none). A two-way mixed model ANOVA with Group (none-none, rsvp-rsvp, rsvp-none, early-adaptation consistent, and late-adaptation consistent) and Block (20 recall blocks) as fixed factors and participant as a random factor showed a significant main effect

of Group ($F_{4,100}$ = 4.22, $p$ < 0.01, $\eta_p^2$ = 0.01), indicating reduced hand angle in the rsvp-none group compared to all the other groups (all $p$'s < 0.02), but no differences among the other groups (all $p$'s > 0.34). There was a significant main effect of Block ($F_{19,1900}$ = 189.28, $p$ < 0.01, $\eta_p^2$ = 0.63), indicating the re-adaptation was occurring to offset the abrupt rotation. The Group x Block interaction ($F_{76,1900}$ = 1.17, $p$ = 0.15, $\eta_p^2$ = 0.04) was not significant.

The mean hand angles during recall blocks 3-7 (20 trials) were also significantly different across the groups ($F_{4,100}$ = 3.91, $p$ < 0.01, $\eta_p^2$ = 0.13), suggesting that the group differences emerged early in recall. Figure 3C shows the reduced mean hand angle only in the rsvp-none group compared to the other groups (all $p$'s < 0.01). We did not find any other group differences (all $p$'s > 0.18). The none-none and rsvp-rsvp groups experienced one attentional context throughout the entire adaptation phase, whereas the early- and late-adaptation consistent groups were exposed to both attentional contexts but only for half of the adaptation phase. Thus, the similar recall performance between the replicate groups and the early- and late-adaptation consistent groups suggests that the attentional context was still encoded with limited exposure. Finally, this result further confirmed that the encoding of attentional context was independent of error magnitude, suggesting that the awareness of the perturbation signaled by error feedback is not necessary for associating the attentional context and visuomotor adaptation.

**Explicit awareness of the gradual perturbation emerged later in adaptation**

Although the errors produced by the gradual perturbation were less noticeable than an abrupt perturbation, it was not entirely clear whether or when awareness of the perturbation emerged. Here, we assessed whether participants became aware of the gradual perturbation and, if so, when this occurred. To summarize, we discovered that explicit awareness of the gradual perturbation was more likely to occur mainly after the first half of adaptation, when the errors were larger.

We administered a brief exit survey following the completion of Experiment 2. We obtained verbal responses regarding which experimental phase (early adaptation, late adaptation, washout, or recall) participants first noticed any systematic mismatch between their hand movement and the visual feedback of the cursor. Participants were also able to indicate that they did not notice any systematic change (i.e., "none"). As shown in Figure 3D, most participants reported that they became aware of the perturbation later in the experiment, including late adaptation (n=39, 37.5%), washout (n=38, 36.5%), or even recall (n=9, 8.5%). Only 5.8% (n=6) of participants reported that they noticed the perturbation during early adaptation.

A substantial proportion of participants reported noticing the systematic mismatch between the hand and cursor movements in the washout phase, which did not involve any rotation of the cursor feedback. This suggests that participants were surprised by the large errors that suddenly emerged after the cursor perturbation was removed and misinterpreted this change as the perturbation. Thus, this response was interpreted as an indication that these participants noticed the adaptations to their movements only after the rotation was removed and

therefore did not recognize the gradual perturbation during the adaptation phase. Another subset of participants did not notice any perturbation but attributed their errors to other factors, such as fatigue (n=12, 11.5%). This pattern of the responses was consistent across the groups.

These results suggest that explicit awareness of the gradual perturbation was more likely to occur mainly after the first half of adaptation, when the errors were larger. Most participants were reportedly unaware of the perturbation during early adaptation, and thus were less likely to have relied on explicit learning processes. This was further supported by the gradual increases in hand angle throughout adaptation and the lack of rapid, transient adjustments that are often indicative of explicit strategy use. Therefore, Experiments 1 and 2 provide converging evidence that awareness of the perturbation, which often co-occurs with explicit learning processes, is not likely to be necessary for the association of attentional context and visuomotor adaptation.

## Experiment 3

### Impaired re-learning is dependent on changes in attentional context rather than the specific task requirements

Experiment 3 examined whether the impaired recall performance observed in Experiments 1 and 2 was due to the shift from divided to undivided attention or changes to the specific task requirements. In Experiment 3, we expected that the inconsistent attentional context group (search-none) would show reduced adaptation compared to the consistent attentional context groups (none-none and

search-search). We further hypothesized that the search-rsvp group would show equivalent recall performance to the consistent attentional context groups (none-none and search-search) but better performance than the inconsistent attentional context group (search-none). This outcome would provide support for the hypothesis that the change in attentional context was the critical factor underlying the impairments to recall performance. Conversely, if changes in the task requirements were driving the impairments to recall performance, we would expect reduced adaptation in both the search-none and search-rsvp groups relative to the none-none and search-search groups. Our results supported the hypothesis that dual-tasking per se, not specific stimuli or tasks determined the consistency of attentional context.

As shown in Figure 4B, the recall performance of the search-none group (red curve) appeared consistently worse than the other groups following the onset of the abrupt 45 deg rotation (Blocks 71-90). A two-way mixed model ANOVA with Group (none-none, search-search, search-none, and search-rsvp) and Block (20 blocks) as fixed factors and participant as a random factor revealed significant main effects of Group ($F_{3,36}$ = 5.02, $p$ < 0.01, $\eta_p^2$ = 0.02) and Block ($F_{19,684}$ = 24.77, $p$ < 0.01, $\eta_p^2$ = 0.38) but no Group x Block interaction ($F_{57,684}$ = 1.04, $p$ = 0.40, $\eta_p^2$ = 0.07). The Block effect indicated a progressive increase in hand angle to offset the cursor rotation. Post-hoc comparisons among the groups indicated lower hand angle in the search-none group in relation to the none-none (6.9 deg, $t_{36}$ = 3.17, $p$ < .01), search-search (6.7 deg, $t_{36}$ = 3.07, $p$ < .01), and search-rsvp groups (7.1 deg, $t_{36}$ = 3.26, $p$ < .01). We computed the mean hand angle over five blocks 72-76 (20 trials) during the early

stage of recall (Figure 4C) and compared among the groups with a one-way ANOVA. This analysis revealed significant group differences ($F_{2,27}$ = 8.12, $p$ < 0.01, $\eta_p^2$ = 0.37), indicating reduced hand angle in the search-none group compared to the none-none (5.4 deg, $t_{27}$ = 2.44, $p$ = 0.02) and rsvp-rsvp groups (8.3 deg, $t_{27}$ = 4.00, $p$ < .01). There were no other differences (all p's > 0.85).

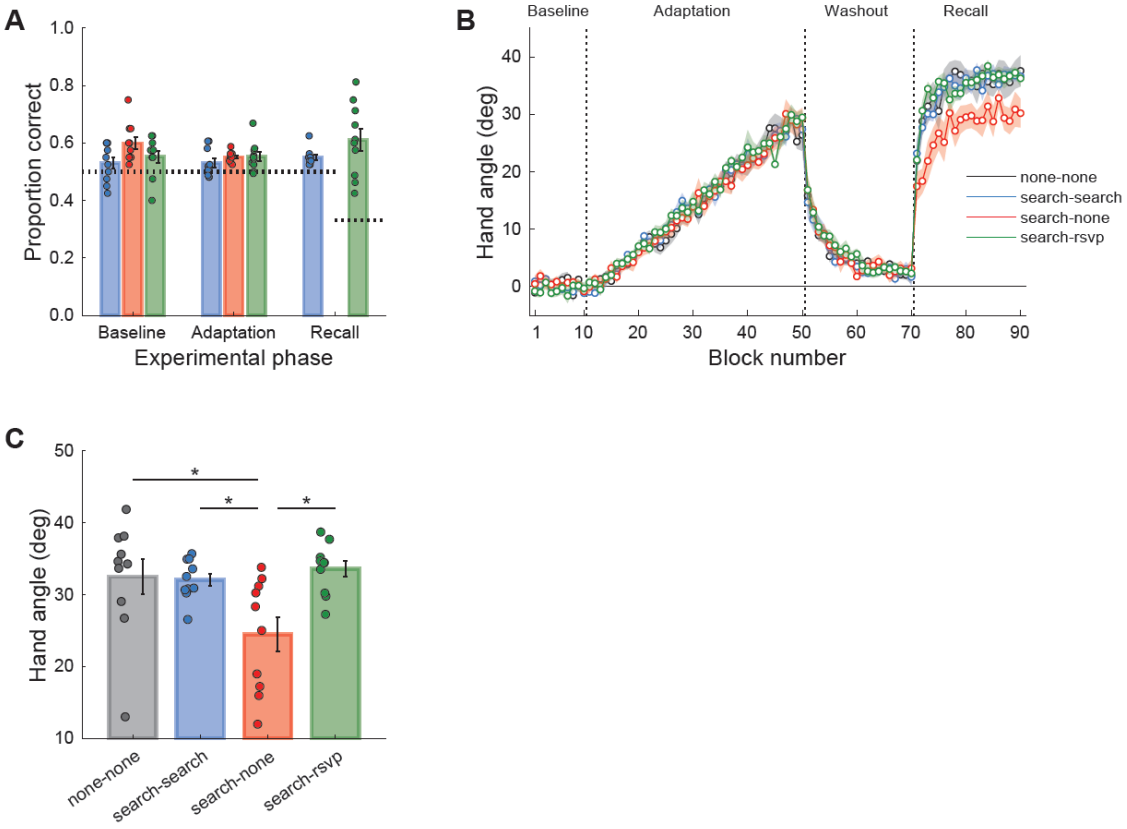


**Figure 4. Experiment 3 results. (A)** RSVP accuracy for the search-search (blue), search-none (red), and search-rsvp (green) groups during the baseline, adaptation, and recall phases. All groups performed above the chance level (0.5 or 0.33; dotted lines). The error bars indicate the standard error of the mean (SEM). **(B)** Hand angle for the none-none (black), search-search (blue), search-none (red), and search-rsvp (green) groups during each block of the baseline, adaptation, washout, and recall phases. Shaded areas indicate the SEM. **(C)** Mean hand angle for recall blocks 3-7 (20 trials). The error bars indicate the SEM. The asterisks indicate significant group differences at the $p$ < 0.05 level. See text for additional details.

These results suggest that the change in attentional context from divided to undivided attention degraded the recall performance. Importantly, the recall

performance of the search-rsvp group was not different from those of the none-none and search-search groups but better than the search-none group, suggesting that visuomotor adaptation to a gradual perturbation under one set of attentional demands (e.g., distributed, spatial) was transferred to another (e.g., localized, temporal). Therefore, we conclude that re-learning was impaired by the change in attentional context from divided to undivided attention but not changes to the secondary task requirements, which engaged different types of visual attention.

## DISCUSSION

One of the major roles of visuomotor adaptation is to adjust movements for timely and effective interactions with objects in dynamic environments (e.g., Wolpert et al., 2011; Huberdeau et al., 2015). Motor learning processes must be flexible and robust to endure variations in environmental conditions. In the current study, participants performed a goal-directed reaching movement to a visual target while a cursor perturbation was gradually incremented each trial. Unlike our previous studies, participants were not exposed to the 45 deg cursor perturbation until the last 10 trials of the adaptation phase, although the recall phase employed only the 45 deg perturbation. Comparable adaptation occurred in response to the gradual perturbation regardless of whether participants performed under single or dual task conditions, which we referred to as the attentional context. Re-learning was impaired when the attentional context changed from a dual task (divided attention) during the initial adaptation to a single task (undivided attention) during recall. This result was counterintuitive in that removing the secondary task resulted in

degraded visuomotor adaptation. The result was also replicated even when the secondary task was performed during only half of the initial adaptation trials and when the type of the secondary task switched from visual conjunction search to RSVP. Our results suggest that the attentional context serves as a cue that aids the recall of previously acquired learning, and does so without necessarily requiring the learner's explicit awareness.

**Different contributions of explicit and implicit learning processes to the abrupt and gradual visuomotor adaptation**

Explicit and implicit learning processes have often been compared using visuomotor adaptation to an abrupt or a gradual perturbation (e.g., Galea et al., 2010; Hwang, Smith, & Shadmehr, 2006). While a gradual adaptation is suggested to occur without awareness and, thus, is primarily assumed to rely on implicit learning processes and mitigate explicit cognitive strategies (Kagerer et al., 1997; Klassen et al., 2005), other work has shown that people attempt to explicitly re-aim their movements when visuomotor rotations are gradually imposed (Butcher et al., 2017). This may occur because the contributions of implicit learning tend to be saturated (Kim et al., 2018; Morehead et al., 2017; Wei & Kording, 2009). Explicit re-aiming tends to scale with the size of the perturbation when a consistent magnitude of visual error is produced (Hutter & Taylor, 2018), making it a feasible strategy for counteracting a small but consistent bias introduced by a gradual perturbation. Implicit learning is most sensitive to small errors (< 8 deg), reducing drifts in performance and allowing

for incremental errors to be updated, unlike an explicit re-aiming that enables fast responses to large discontinuous changes (Hutter & Taylor, 2018).

It has been proposed that visuomotor adaptation results from the coordination and competition among multiple learning processes, such as slow versus fast processes (Smith et al., 2006), error-based learning (Helmholtz, 1962; Shadmehr & Mussa-Ivaldi, 1994; Krakauer et al., 2000) versus reinforcement learning (Dam et al., 2013; Izawa & Shadmehr, 2011), and implicit versus explicit processes (Hwang et al., 2006; Malfait & Ostry, 2004). One common feature of the various frameworks is that both implicit and explicit processes contribute to visuomotor adaptation. For explicit strategies to operate, a certain form of awareness of the cursor perturbation is necessary (Hegele & Heuer, 2010; Heuer & Hegele, 2011). This can be triggered and controlled by explicit instructions (e.g., Mazzoni & Krakauer, 2006; Sülzenbrück & Heuer, 2009; Taylor & Ivry, 2011), cueing (e.g., Morehead et al., 2015), or visual feedback about task outcomes (e.g., Hinder et al., 2008). On the other hand, implicit learning processes produce automated and limited-magnitude responses by operating on sensory prediction errors (Kim et al., 2018; Morehead et al., 2017; Taylor & Ivry, 2011).

Previous studies have suggested that explicit and implicit processes play different roles in initial adaptation versus recall. For example, both awareness and cognitive strategies are correlated with adaptation performance (Werner et al., 2015). During adaptation, participants with explicit knowledge about the perturbation showed better performance, reflected by learning indices, compared to those without explicit knowledge (Hwang et al., 2006). This finding indicates the

important contributions of awareness and cognitive strategy use to visuomotor adaptation. Importantly, however, the facilitatory effects of explicit knowledge may not be observed during recall (Werner et al., 2015).

**Minimal contribution of awareness and re-aiming strategies to the gradual visuomotor adaptation**

In the current study, hand angles were initially small and gradually increased as adaptation progressed, indicating that participants modified their reach direction at a constant rate to compensate for the imposed perturbation. The rate of adaptation (~0.2 deg/trial) was lower than the rate of the gradual cursor perturbation (0.3 deg/trial), leading to the accumulation of errors throughout the adaptation phase. This may have triggered participants' awareness of the cursor perturbation and encouraged them to use an explicit re-aiming strategy to cancel the error (e.g., Butcher et al., 2017). In all three experiments, however, hand angles during the adaptation phase did not show any notable discontinuity, suggesting that it is unlikely that participants began to use an explicit re-aiming strategy in the middle of the adaptation phase.

In Experiment 2, we could also directly compare the hand angle when concurrently performing a secondary task during the early adaptation phase (producing smaller errors, mean: 5.13 deg, SD: 0.23 deg) compared to the late adaptation phase (producing larger errors, mean: 9.80 deg, SD: 0.47 deg). Recall performance was equally good in both conditions, suggesting that the association of attentional context and visuomotor adaptation occurred even when error signals

were small and self-reported explicit awareness was limited. Given the previous reports that implicit adaptation tended to saturate at around 20 deg on average (e.g., Kim et al., 2018; Morehead et al., 2017), we cannot completely rule out the possibility of explicit strategy use, at least in the late adaptation phase. However, the comparable adaptation responses and secondary task performance between the early- and late-adaptation consistent groups and the awareness reports in Experiment 2 provide converging evidence that awareness and explicit re-aiming strategies that develop following exposure to large, systematic errors were minimally involved in the association of the attentional context and visuomotor adaptation in the current study.

**Attentional context is encoded independent of dual task costs**

In all experiments, the different groups of participants did not show evidence of distinct adaptation responses or trade-offs in secondary task performance during the adaptation phase. Yet, in one of our recent studies (Wang et al., 2022), dual task costs were found in young adults but not older adults when trial-by-trial feedback about the accuracy of the secondary task was provided. Our study design, which did not provide secondary task feedback, may have allowed participants to better manage both tasks while avoiding attentional bottlenecks. Importantly, however, in both the current work and Wang et al, (2022), we consistently found that re-learning was impaired when the attentional context changed between adaptation and recall. These results collectively suggest that the attentional context is encoded even when there is interference between the two concurrent tasks. A novel

implication of our findings is that visuomotor adaptation can be impaired when the task difficulty is made easier in the recall phase (by removing the secondary task) than in the initial adaptation.

**Attentional context is encoded as a generic task structure**

Using an abrupt adaptation paradigm, we previously demonstrated the impact of changes to attentional context on visuomotor adaptation, tested both in an immediate recall (Song & Bédard, 2015) and a delayed recall (Im et al., 2016). Furthermore, the impaired re-learning in the altered attentional context was consistently observed when the secondary task was varied between RSVP and brightness or sound discrimination tasks (Song & Bédard, 2015). Although the defining features of target items varied between adaptation (e.g., color) and recall (brightness or sound pitch), a similar serial presentation of stimuli was used in this previous study, requiring the allocation of attention to the fixed location over time. Thus, it was possible that the sustained, temporal attention for monitoring the sequential presentation was the key factor in encoding the attentional context during visuomotor adaptation. However, the results of Experiment 3 suggest that this was not the case. The visual conjunction search task in Experiment 3 required attention to be spatially distributed to scan different locations of the visual array, where all items were presented simultaneously. By using visual conjunction search, we showed that the (in)consistency of the attentional context (i.e., shifting from divided attention to undivided attention), not the maintenance of temporal attention, was the key factor in determining whether re-learning would be effective

or impaired.

Separate mechanisms are proposed to underlie attentional processes directed toward specific events in time versus space (e.g., Coull & Nobre, 1998; Doherty et al., 2005; MacKay & Joula, 2007), likely mediated by distinct neural mechanisms (Griffin, Miniussi, & Nobre, 2001). For example, there is evidence supporting the independent effects of spatial and temporal cues on target detection and discrimination in attention tasks, such as a visual search task (e.g., Coull & Nobre, 1998). Furthermore, previous work collectively demonstrates the additive effects of temporal and spatial cues (e.g., Coull & Nobre, 1998; Doherty et al., 2005; MacKay & Joula, 2007; Milliken et al., 2003), suggesting that temporal and spatial attentional modes are independent processes. By demonstrating that visuomotor adaptation was unimpaired when maintaining the same attentional context but engaging different modes of attention, the results in Experiment 3 imply that the generic task structure (e.g., single- or dual-task), rather than specific task requirements or environmental features, was encoded as an internal cue. The current findings are in line with the notion of structural learning, in which people tend to learn a general form and structure of the rules that govern a set of tasks, rather than the notion of parametric learning, where people become familiar with the parameters of a specific task (for review, Braun et al., 2010). In the current study design, participants could have avoided decrements in visuomotor adaptation and recall by relying on regularities of the "nested" task structures in which they moved a mouse cursor while performing the secondary task, then made a key-press as a one task sequence.

## CONCLUSION

The current study demonstrates that the association between attentional context and visuomotor adaptation occurs without explicit awareness. It also demonstrates that what is encoded as attentional context is the internal 'processing' structures such as dividing attention to a secondary task rather than task-specific parameters. Thus, visuomotor adaptation acquired under one attentional context appears to generalize across environments, without being limited by episodic memory of the specific task or external constraints. The robust and generalizable effects of attentional context on visuomotor adaptation may help to improve training or rehabilitation programs. Our findings suggest that learners need not be restricted to less attention-demanding conditions and may benefit from performing in the same attentional context during the initial stages of learning. If the same internal attentional states encountered in the learning environment are engaged at recall, they can serve as an effective retrieval cue.

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## Table Captions

**Table 1**. **Participant demographics for Experiments 1-3.** N is the number of participants in each experiment; n is the number of participants per group. Standard deviations are indicated for age.

**Table 2**. **Experiment 1 task details.** Participants performed the primary visuomotor rotation task and secondary RSVP task depending on group assignment.

**Table 3**. **Experiment 2 task details.** Participants performed the primary visuomotor rotation task and secondary RSVP task depending on group assignment.

**Table 4. Experiment 3 task details.** Participants performed the primary visuomotor rotation task and secondary visual search task or RSVP task depending on group assignment.

## Figure Captions

**Figure 1. Task schematics. (A)** Visuomotor rotation task. Targets appeared one at a time and remained visible for the entire trial. During the baseline and washout phases, the cursor followed the hand normally. During the adaptation phase, the cursor position was rotated counterclockwise (CCW) with respect to the hand, from 0 deg to 45deg with an increment of 0.3 deg. During the recall phase, the cursor position was rotated 45 deg CCW relative to the hand for all trials. **(B)** RSVP task. A sequence of five T's was presented, each for 150 ms in either an upright or inverted orientation and one of five different colors. Participants reported how many target T's (upright, red T's and inverted, green T's) were presented via key press at the end of each trial. **(C)** Visual search task. A search array consisting of either an upright or inverted red T and 16 distractors (blue T's and red L's) was presented for 1500 ms. Participants reported whether the red target T was in the upright or inverted orientation via keypress at the end of each trial.

**Figure 2. Experiment 1 results. (A)** RSVP accuracy for the rsvp-rsvp (blue) and rsvp-none (red) groups during the baseline, adaptation, and recall phases. Both groups performed above the chance level (0.33; dotted line). The error bars indicate the standard error of the mean (SEM). **(B)** Hand angle for the none-none (black), rsvp-rsvp (blue), and rsvp-none (red) groups during each block of the baseline, adaptation, washout, and recall phases. Shaded areas indicate the SEM. **(C)** Mean hand angle for recall blocks 3-7 (20 trials). The error bars indicate the SEM. The

asterisks indicate significant group differences at the $p < 0.05$ level. See text for additional details.

**Figure 3. Experiment 2 results. (A)** RSVP accuracy in the rsvp-rsvp (blue), rsvp-none (red), early-adaptation consistent (orange), and late-adaptation consistent (purple) groups during the baseline, adaptation, and recall phases. All groups performed above the chance level (0.33; dotted line). The error bars indicate the standard error of the mean (SEM). **(B)** Hand angle for the none-none (black), rsvp-rsvp (blue), rsvp-none (red), early-adaptation consistent (orange), and late-adaptation consistent (purple) groups during each block of the baseline, adaptation, washout, and recall phases. Shaded areas indicate the SEM. **(C)** Mean hand angle for recall blocks 3-7 (20 trials). The error bars indicate the SEM. The asterisks indicate significant group differences at the $p < 0.05$ level. **(D)** Proportion of participants that reported being aware of the pertubration within each experimental phase. See text for additional details.

**Figure 4. Experiment 3 results. (A)** RSVP accuracy for the search-search (blue), search-none (red), and search-rsvp (green) groups during the baseline, adaptation, and recall phases. All groups performed above the chance level (0.5 or 0.33; dotted lines). The error bars indicate the standard error of the mean (SEM). **(B)** Hand angle for the none-none (black), search-search (blue), search-none (red), and search-rsvp (green) groups during each block of the baseline, adaptation, washout, and recall phases. Shaded areas indicate the SEM. **(C)** Mean hand angle for recall blocks 3-7

(20 trials). The error bars indicate the SEM. The asterisks indicate significant group differences at the $p < 0.05$ level. See text for additional details.

## Supplemental Data

**Figure S1** - https://figshare.com/s/2e49563212897a2dfe5c

**Figure S2** - https://figshare.com/s/7a31609710f5e1d5180e