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Behavioral/Cognitive

Attention Defines the Context for Implicit Sensorimotor Adaptation

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The sensorimotor system continuously uses error signals to remain precisely calibrated. We examined how attention influences this automatic and implicit learning process in humans (male and female). Focusing first on spatial attention, we compared conditions in which attention was oriented either toward or away from the visual feedback that defined the error signal. Surprisingly, this manipulation had no effect on the rate of sensorimotor adaptation. Using dual-task methods, we next examined the influence of attentional resources on adaptation. Again, we found no effect of attention, with the rate of adaptation similar under focused and divided attention conditions. However, we found that attention modulates adaptation in an indirect manner: The rate of adaptation was significantly attenuated when the attended stimulus changed from the end of one trial to the start of the next trial. In contrast, similar changes to unattended stimuli had no impact on adaptation. These results suggest that visual attention defines the cues that establish the context for sensorimotor learning.

Key words: **cognitive resources; contextual modulation; implicit learning; sensorimotor adaptation; spatial attention**

Significance Statement

In many domains, attention has been found to be a potent modulator of learning. Here, we present an exception. In a series of experiments, we find that sensorimotor adaptation is surprisingly robust, unaffected by manipulations of spatial attention or the availability of cognitive resources. Interestingly, we identified a unique way in which visual attention does influence adaptation: Attended stimuli serve as contextual cues that constrain the expression of motor memory even if the stimuli are not relevant to the adaptation task. Specifically, the generalization of learning was impaired when the attended stimuli changed. Our result suggests that attention constrains the information that will define the learning context for sensorimotor adaptation.

Introduction

Adapting our movements in response to changes in the environment and body is essential for survival. Sensorimotor adaptation involves multiple learning systems, including an implicit system that operates to maintain the calibration of the sensorimotor map and an explicit system that can be flexibly deployed to deploy strategies that minimize performance error (Kim et al., 2021). While explicit processes are critical for volitional changes in behavior, implicit processes operate in an automatic manner to keep the motor execution system precisely calibrated.

Prior studies have shown that sensorimotor learning systems are sensitive to attentional manipulations. For example, the rate of adaptation is reduced when participants are engaged in a concurrent, secondary task. This phenomenon has been observed in many types of sensorimotor adaptation tasks including prism adaptation (Redding and Wallace, 1996), visuomotor rotation (Wang et al., 2022), and force-field adaptation (Taylor and Thoroughman, 2007; Thoroughman et al., 2007). The slower rate of adaptation observed under dual-task conditions is usually attributed to a limitation within the explicit system (Taylor and Ivry, 2014; Song, 2019). For example, the cognitive resources required to complete the secondary task limit resources available to discover and evaluate a strategy that will counteract the perturbation.

The implicit recalibration process, on the other hand, is assumed to operate in an automatic manner. It uses a forward model to predict the sensory consequences of a movement and the sensory prediction error, the difference between the predicted and actual feedback, to recalibrate the system. Implicit adaptation has been demonstrated to be a remarkably robust process. It is observed even in situations in which there is no explicit task error or when participants are instructed to disregard the feedback and move directly to the target (Mazzoni and Krakauer, 2006; Morehead et al., 2017; Kim et al., 2018).

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However, the impact of attention on the implicit adaptation system remains unclear. While we tend to assume that automatic processes do not utilize cognitive resources, this proposal has never been systematically explored in the domain of implicit sensorimotor adaptation. There is a substantial body of evidence showing that implicit processes can be susceptible to the effects of divided attention. For instance, visual priming is diminished when participants are engaged in a secondary task, an effect attributed to a reduction in the depth of processing of the priming stimuli (Schmitter-Edgecombe, 1996; Otsuka and Kawaguchi, 2007; Prull et al., 2016). Divided attention might impact implicit adaptation in a similar way.

Beyond the cognitive resource hypothesis, there are other ways in which attention could influence implicit adaptation. For instance, the focus of visuospatial attention could have a modulatory effect on the processing of a visual feedback signal. This hypothesis is motivated by studies in which multiple feedback cursors are simultaneously presented during sensorimotor adaptation (Kasuga et al., 2013). Under these conditions, the functionally effective error signal is a composite signal, one that corresponds to the averaged error conveyed by the feedback. However, if the participant is instructed that one of the feedback cursors is more task-relevant, the implicit system allocates a larger weight to this input when calculating the composite error (Tsay et al., 2024).

A third way by which attention might influence implicit adaptation is through contextual mediation. Motor memories are, to some degree, context specific, with the manifestation of the memory reduced when the context changes (Shea and Morgan, 1979; Heald et al., 2021). For example, there is limited generalization of the adapted behavior when the target changes shape (Poh et al., 2021) or when participants switch from reaching with their arm to reaching with a tool (Kluzik et al., 2008). We hypothesize that attention might influence how the context is established: Attended stimuli may serve as cues that define the context for learning. Thus, the manipulation of attention might result in a contextual change, with a consequence being reduced expression of adaptation.

In the current study, we examine if and how attention influences implicit sensorimotor adaptation, systematically evaluating cognitive resource, visuospatial attention, and context mediation hypotheses.

Materials and Methods

Participants

All experiments were performed online. Using the website prolific.co, we recruited a total of 859 participants (age, 27.3 ± 4.9 years old; 492 females), with the only inclusion criteria being that the participant was right-handed with normal or corrected-to-normal vision based on their responses to the Prolific prescreening questionnaire. For the analyses, we excluded participants who failed to meet our a priori performance requirements on the attention tasks (see below). This resulted in a final pool of 626 participants (355 females). Table S1 provides details on the sample size for each experiment. The participants were paid ∼$8/h.

Apparatus

The experiments were run on OnPoint, an online platform we have developed for studies of sensorimotor control and learning (Tsay et al., 2021b). OnPoint is written in JavaScript and accessed via the Google Chrome web browser. For these studies, the participant accesses OnPoint from their personal computer. Visual stimuli are presented on their monitor, and the movement data are based on finger movements across their trackpad. The data are stored on Google Firebase, a cloud-hosted database. The instructions were provided over a series of text screens. To ensure that participants read the instructions, a key code was embedded on one page, and the participant was required to enter the code before they could start the task.

Procedure

Clamp rotation task. We used clamped feedback in a visuomotor adaptation task, a method designed to isolate learning to implicit sensorimotor adaptation (Morehead et al., 2017; Kim et al., 2018). To start each trial, the participant moved a white cursor into a white start circle (radius, 1% of the screen height) positioned in the center of the screen. After 500 ms, a blue target circle (radius, 1% of the screen height) appeared. The radial position of the target was set to 40% of the screen height, and angular position of the target was fixed at −45° (where 0° corresponds to the rightward direction). Given that the magnitude of implicit adaptation does not vary systematically with target position (Wang et al., 2024b), we opted for a single target location to reduce variability across participants. We chose to have the target appear along a diagonal (−45°) rather than along a cardinal axis.

The participant was instructed to produce a rapid, out-and-back movement, attempting to intersect the target. Feedback, when presented, could take one of the two forms. On veridical feedback trials, the feedback cursor was congruent with the hand position until the movement reached the target distance. At that point, the cursor was frozen for 50 ms before disappearing. On perturbation trials, we used endpoint clamped feedback. Here the feedback cursor disappeared at the movement onset and only reappeared when the radial distance of the movement reached the target distance. The angular position of the feedback cursor was invariant, displaced by 15° from the target (except in the condition in Experiment 1 (Exp 1) in which the clamp size was 30°). That is, the position of the cursor is not contingent on the position of the hand. The feedback cursor remained visible for 50 ms. The direction of the clamp was randomized across trials. Movement time was defined as the interval between the hand leaving the start circle and when the radial distance of the hand reached the target distance (40% of the screen height). If movement time was >500 ms, the message "Too Slow" was presented on the screen and remained visible for 500 ms. To help guide the participant back to the start location, a white cursor (radius, 0.6% of screen height) appeared when the hand was within 30% of the target distance.

Just before the start of the trials with clamped feedback (see below), we provided a set of instructions to describe this atypical perturbation. The instructions stated that the angular position of the cursor would no longer be linked to their movement but rather would be fixed on all trials. The participant was to always reach directly to the target, ignoring the cursor. These instructions were repeated to make sure the participant understood the nature of the error clamp. For the first 10 trials with clamped feedback, we used a large clamp size of ±30/±90/180° to make clear to the participant that the feedback position was not under their control. After this familiarization phase, an instruction screen asked the participant to indicate if they were aiming for the target or another location. If the participant indicated they were reaching somewhere other than toward the target, the experiment was terminated. The "sensory prediction error" introduced by clamped feedback causes the angular direction of the next movement to be shifted in the opposite direction (Avraham et al., 2022; Wang et al., 2024a). This change occurs automatically and outside awareness, with all the hallmarks of implicit adaptation.

We applied the same trial structure for all experiments except Exp 1e and 1f (see below). There was a total of 560 trials beginning with a 10-trial baseline block with veridical continuous feedback. The next 10 trials were used to familiarize the participants with the clamped feedback procedure. Then the secondary task was described. The remaining 540 trials were divided such that the ±15° clamped feedback cursor appeared on two-third of the trials and was absent on one-third of the trials. The conditions were counterbalanced within each set of 30 trials.

While relatively new, online studies of sensorimotor adaptation have shown that key features of implicit adaptation (e.g., learning rate and asymptote) are strikingly consistent between online and in-person setups (Tsay et al., 2021b). Online and in-person studies produce similar effects when examining variables such as feedback timing (Wang et al., 2024a), planned versus executed movement (Kim et al., 2022), interactions between implicit and explicit systems (Albert et al., 2022), and context (Avraham et al., 2022). Taken as a whole, the burgeoning online adaptation literature underscores that core principles of implicit adaptation are robust and generalize across different experimental setups. As such, we are confident that the online platform is a reasonable approach for exploring the role of attention on sensorimotor adaptation.

We next describe the design of the attentional manipulations for each experiment.

Exp 1a and 1b. We applied a within-participant design in Exp 1 to examine the effect of spatial attention. A spatial cueing task was used to manipulate spatial attention. On each trial in Exp 1a, an arrow was presented within the target, pointing to either the left or right. When the endpoint clamp feedback appeared, two red bars were displayed, one on either side of the target. The angular deviation of the two bars was 15°, such that the feedback cursor on clamp trials was positioned beneath one of the red bars (Fig. 1*a*). Each bar was oriented either vertically or horizontally, and the participant's task was to indicate the orientation of the cued bar. The feedback cursor and bars were only visible for 50 ms, after which the cursor disappeared, and the bars were transformed into two crosses for 90 ms. The latter served to mask the orientation of the bars, precluding visual aftereffects that could be used for the discrimination task. After the mask disappeared, a message appeared on the screen, indicating that the participant should press the "e" key with the left hand if the cued bar was horizontal or the "r" key with the left hand if the cued bar was vertical. Feedback on the orientation discrimination task ("good" or "wrong") was presented for 700 ms before the start of the next trial. We refer to the condition in which the cued bar and feedback cursor appeared at the same location as "attended" and the condition in which the cued bar was on the opposite side of the clamp cursor as "unattended," counterbalanced during the training session. Our key experimental question is whether adaptation will be greater in the attended condition compared with the unattended condition.

Exp 1b followed the same procedure as Exp 1a with the only difference being that the clamp and bars were shifted 30° from the target.

Exp 1c and 1d. In Exp 1a and 1b, we assumed that on attended trials, the clamped feedback cursor and cued red bar would fall within the focus of spatial attention. However, these two objects appeared at distinct locations in space; it may be that the focus of attention was associated with an object (i.e., the red bar) rather than a location (Logan, 1996; Roelfsema et al., 1998). To address this issue, we presented the red bar at the same radial and angular position as the feedback cursor in Exp 1c (Fig. 1*d*). Thus, on attended trials, the red bar was now presented within the feedback cursor. All other aspects of the design remained the same as in Exp 1a.

In Exp 1d we presented two clamped cursors symmetrically positioned around the target and embedded one red bar within each cursor (Fig. 1*e*). The arrow embedded in the target indicated which red bar was relevant for the orientation report. With this design, one location, and thus cursor, is more task-relevant than the other. We asked if adaptation would be induced with this type of display or if the "balanced" feedback would eliminate adaptation (Kasuga et al., 2013).

Exp 1e and 1f. The results of Exp 1a–1d failed to find any effect of spatial attention on implicit sensorimotor adaptation. One concern, however, is that we used a trial-by-trial design in each experiment: With such designs, the size of adaptation is relatively small and thus may have limited our sensitivity to detect differences between the attended and unattended sides.

To allow adaptation to accumulate across trials, we used a pseudoblock design in Exp 1e, with the clamped cursor appearing on the one side on 80% of the trials (CW or CCW, counterbalanced across participants). We again presented two bars on each trial, and an arrow indicated which bar was relevant for the orientation judgment (Fig. 2*a*). We created attended and unattended blocks by manipulating the probability of the direction of the arrow, with the probability of the clamp location and cued direction independent of each other.

In the attended condition, the direction of the arrow cued the expected side of the cursor on 80% of the trials. As such, the cursor and cued bar were on the same side on 68% of the trials, 64% of which on the high probability side and 4% on the low probability side. For the other 32% of trials, the cursor and cued bar were on opposite sides, with the cursor on the high probability side on 16% of the trials and on the low probability side on the other 16%. In the unattended condition, the direction of the arrow cued the expected side of the cursor on 20% of the trials. As such, the cursor and cued bar were on the same side on only 32% of the trials, 16% of which on the high probability side and 16% on the low probability side. For the other 68% of trials, the cursor and cued bar were on opposite sides, with the cursor on the high probability side on 64% of the trials and on the low probability side on the other 4%.

Each participant completed two blocks of trials, one for the attended condition and one for the unattended condition. Each block included 10 baseline trials, 10 familiarization trials with clamped feedback, and 100 perturbation trials. The order of the attended and unattended blocks, the direction of the arrows, and the target positions (±45, ±135°) associated with attended/unattended session were counterbalanced across participants.

In Exp 1f, two cursors were presented, one on each side of the target (Fig. 2*d*). The arrow pointed in one direction on 80% of the trials and in the other direction in 20% of the trials. Should there be any attention effect, it could accumulate across trials. In the control session, the direction of the cue was randomized (50/50 session). The order of the blocks, the direction of the arrow, and the target positions (±45°, ±135°) were counterbalanced across participants.

Exp 2. Exp 1 focused on the influence of spatial attention on implicit adaptation. In Exp 2, we shift our focus, asking if adaptation is influenced by the availability of cognitive resources (Otsuka and Kawaguchi, 2007; Prull et al., 2016; Song, 2019). Specifically, we assume that the secondary bar discrimination task draws on cognitive resources. If adaptation also draws on the same resource pool, then adaptation might be attenuated by the inclusion of the secondary task.

We addressed this question in Exp 2 by comparing adaptation under single and dual-task conditions. We opted to use a between-participant design so that the participants could adopt a consistent task set (either single-task or dual-task) for the entire experiment. A 15° clamped cursor was presented on two-third of the trials (CW/CCW counterbalanced) and absent on one-third of the trials. We used a secondary task here, simply asking participants to report the side of the clamped cursor feedback or report that it was not presented (Fig. 3*a*). Depending on the accuracy of the response, the message "good" or "wrong" was presented for 700 ms after each response. In the single-task condition, the same conditions were presented, but now the participant was instructed to ignore the feedback cursor (as in a "standard" clamp experiment). To roughly equate the motor requirement with that of the dual-task condition, we required the participant to press the "e" key after each trial, followed by the message "good."

Exp 3. In Exp 3, we further examined whether the processes involved in implicit adaptation are impacted when the availability of cognitive resources is manipulated in a between-participants design. We again used an orientation discrimination task, presenting a red bar at the target location with the onset of the feedback cursor (Fig. 3*b*). Both were visible for only 50 ms, with the red bar then transformed into a cross for 90 ms. To manipulate resources, we varied the difficulty of the secondary task (Wickens, 1981; Hirst and Kalmar, 1987), asking the participant to either report the orientation of the bar on the current trial (zero-back condition) or report if the orientation on the current trial matched the orientation of the bar on the previous trial (one-back condition). We also included a single-task control condition in which the participant was told to ignore the red bar.

Exp 4. As another test of the central resource idea, we used an auditory pitch discrimination task as the secondary task in Exp 4. At the

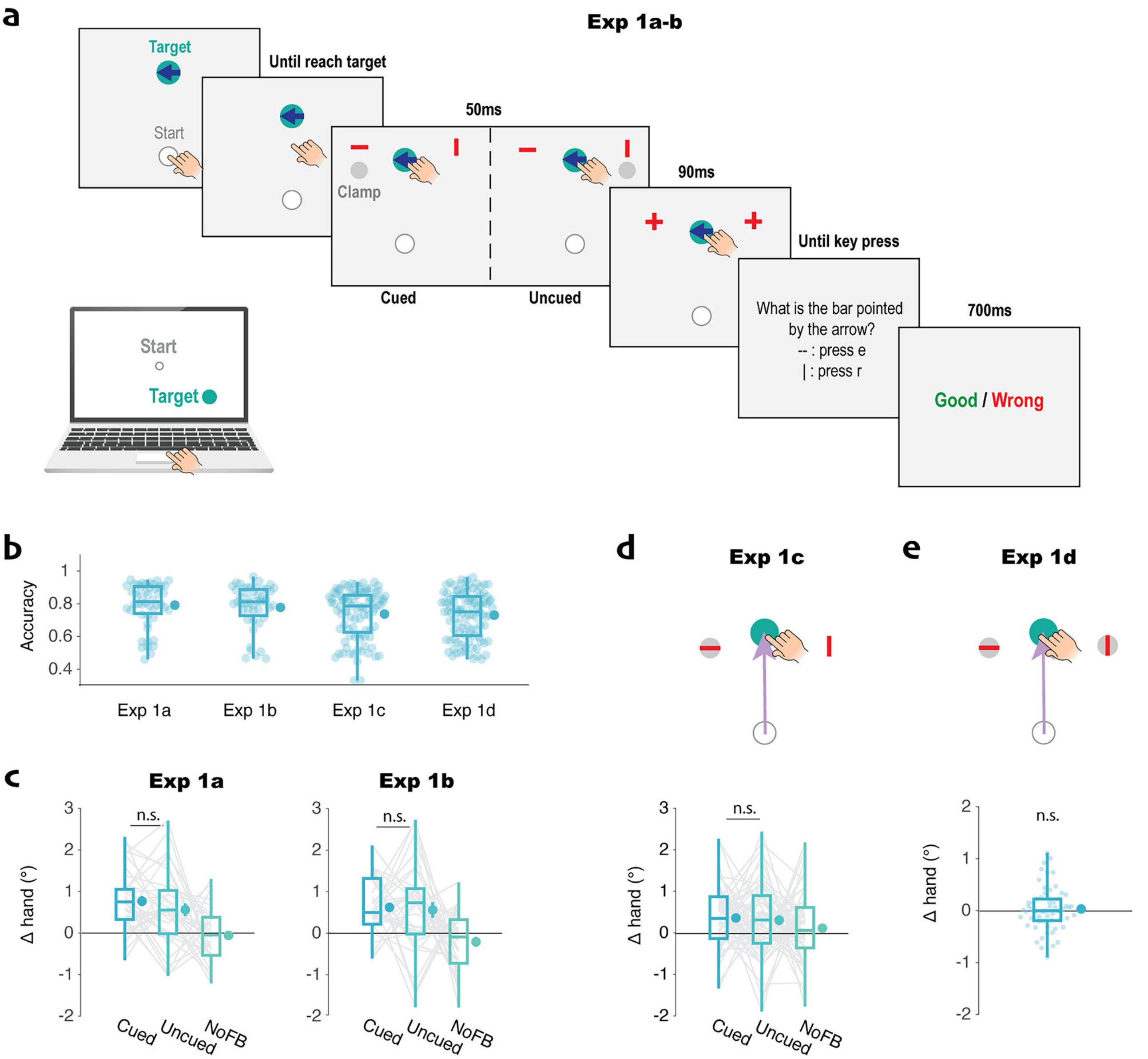

Figure 1. Trial-by-trial implicit adaptation is not modulated by visual spatial attention. ***a***, Event sequence of Exp 1a, Participants made center-out movements to a visual target by moving their finger across a trackpad. The arrow on the target indicated the trial-relevant bar for the orientation discrimination task. Uncued refers to trials in which the clamp appeared on the opposite side of the reported bar. The bar and clamped feedback cursor were presented simultaneously when the radial distance of the hand movement reached the target. After 50 ms, the bars were converted to "+" signs, serving as pattern masks. Following keyboard entry to indicate the orientation of the cued bar, feedback was provided. Note that we depict the target at 90° for illustration purposes, but the actual location was −45° (lower-right corner). ***b***, Accuracy on the orientation discrimination task for Exp 1a–1d. ***c***, The Δhand angle in Exp 1a and 1b. The presence of either a 15° (left) or 30° (right) clamped cursor induced trial-by-trial implicit adaptation. The magnitude was similar for the attended and unattended conditions. ***d***, The Δhand angle (top row) and example of stimulus display showing bar embedded in clamped cursor (bottom row) for Exp 1c. Again, adaptation was not influenced by the focus of spatial attention. ***e***, Adaptation in response to the cursor on the cued side was abolished when a second clamped cursor was presented on the opposite side in Exp 1d. For the boxplot, whiskers extend to ±standard deviation. The dot on the right of the box indicates the mean, and the error bar indicates the standard error. This format is used in all figures.

movement onset, a series of three 40 ms pure tones were played, separated by 50 ms (Fig. 3*c*). The pitch of two of the tones was 261 Hz (middle C), and the other was 522 Hz (an octave higher). For the dual-task group, the participants indicated the ordinal position of the odd tone by choosing from three options using key press (first/second/third). Performance on the tone task was indicated by a feedback message (good/wrong) presented for 700 ms after each response. For the single-task group, the participants ignored the auditory stimuli.

Exp 5. Our final test of the resource involved a within-participant design. On 50% of the trials, the target changed from blue to orange in synchrony with the onset of the clamped feedback cursor and then back to blue when the cursor disappeared for 90 ms (Fig. 3*d*). For the other 50% of the trials, the target color remained blue throughout the trial. The participant reported if the target had changed color (yes/no) by key press.

Exp 6. The results of Exps 1–5 suggested an alternative account of how attention might impact implicit adaptation, namely, that attention might alter the context and create scenarios in which adaptation is attenuated due to a contextual change (Shea and Morgan, 1979; Heald et al., 2021, 2022; Avraham et al., 2022). In particular, when the focus of attention during action planning (i.e., target onset) is different from the focus at the time of feedback processing (i.e., the clamp onset), different internal models are created, and adaptation will be attenuated due to imperfect generalization (Haruno et al., 2003; Howard et al., 2013; Heald et al., 2022).

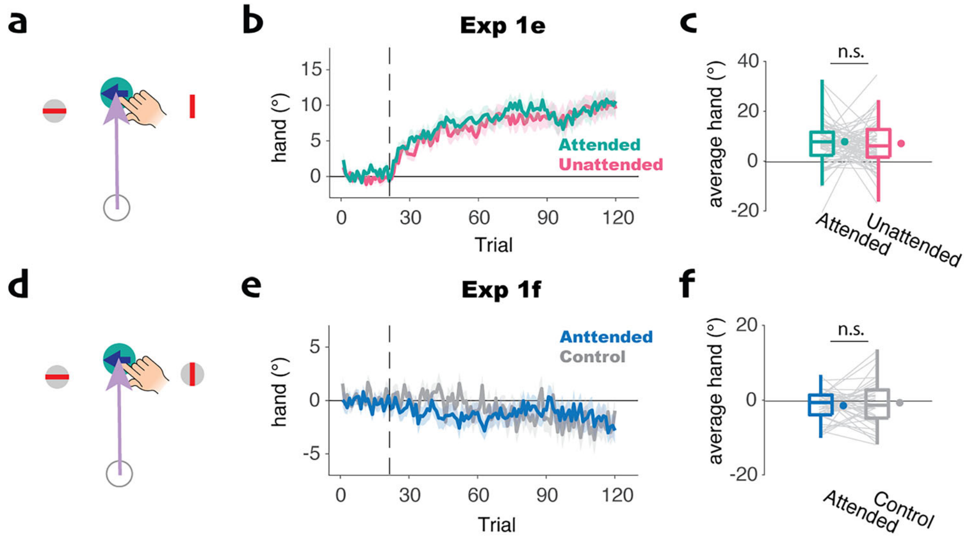

Figure 2. Accumulated adaptation is not modulated by visuospatial attention. ***a***, Representative display for the attended condition Exp 1e. The clamp appeared on the cued side on 80% of the trials and on the opposite side for the other 20%. These percentages were reversed for the unattended condition. ***b***, The learning curve with the vertical dashed line indicating the clamp onset. We applied a cluster-based permutation test to compare the learning curves. However, no significant cluster was found. ***c***, The average hand angle across trials in which the clamp was presented. No significant difference was observed in the average hand angle. ***d–f***, Similar to ***a–c*** but for Exp 1f. Two clamped cursors were presented with the arrow cuing the target on the one side on 80% of trials (experimental condition). In the control condition, the direction of the arrow was randomized (50% each direction). Neither condition resulted in significant adaptation.

We tested this hypothesis in Exp 6 by manipulating the consistency of the focus of attention within and between trials. A red bar, oriented vertically or horizontally, was embedded within the target at the target onset and disappeared at the movement onset. A second bar, either with the same or different orientation appeared within the target at the feedback onset (Fig. 4*a*). The participants were always asked to report the orientation of the second bar; as such, the first bar was task irrelevant, but we assume it is processed with the target and thus provides a contextual cue.

For one group of participants, the orientation of the second bar on trial $N-1$ was always the same as the orientation of the first bar of trial N. For the other group, the orientation of the second bar on trial $N-1$ was always different from the orientation of the first bar of trial N. We hypothesized that adaptation would be attenuated in the second group since the internal model retrieved at the onset of trial n is different from the internal model that had been updated on the previous trial (Fig. 4*b*). For both groups, the two bars within a trial can be either the same or different (counterbalanced). In this manner, the full design contains four conditions regarding the consistency of the bar orientation within and across trials (Fig. 4*b*, AA→A, AB→B, AB→A, AA→B).

Analysis

We first assessed the accuracy of each participant on the secondary task in the dual-task conditions. We set an accuracy criterion of 70% or greater on the secondary task for inclusion in the main analyses, a criterion that was reached by ∼80% of the participants (see Table S1 for inclusion information for each experiment). Our reasoning here was that low accuracy might indicate that the participant had not paid sufficient attention to the secondary task, a prerequisite for assessing the impact of attention on implicit adaptation.

For the analyses of adaptation, the hand angle was defined as the angle between a line from the start location to the target and a line from the start location to the hand when the movement amplitude of the cursor had reached the target distance. Angular values were transformed such that positive angles correspond to values in which the hand direction is in the opposite direction of the clamped feedback relative to the target, the signature of adaptation. We excluded trials in which the movement duration was longer than 500 ms or the reach error was larger than 60°. Participant with ∼30% invalid movements were excluded from all subsequent analyses (∼5%).

To analyze adaptation in the trial-by-trial designs, we calculated the change of the hand angle after each trial. Specially, the learning expressed on trial n is calculated by subtracting the hand angle on trial $n+1$ from the hand angle on trial n. We used two methods to analyze adaptation in the block design of Exp 1e and 1f. First, we applied a cluster-based simulation test on the learning curve, looking for epochs that showed a significant difference between the attended and unattended conditions (Avraham et al., 2021; Wang et al., 2024a). Second, we used a composite measure, averaging the hand angle data across the entire perturbation phase.

T tests and ANOVAs were used for between condition comparisons. For the *t* tests, we report the Bayes factor BF10, to indicate the ratio of the likelihood of the alternative hypothesis (H1) over the null hypothesis (H0) (Schönbrodt and Wagenmakers, 2018; Stefan et al., 2019). A BF10 larger than 3 suggests moderate evidence supporting H1, while a BF10 smaller than 0.33 suggests moderate evidence supporting H0. We also report Cohen's *d* as an estimate of effect size. Before performing the *t* tests or ANOVAs, we excluded data points more than three standard deviations from the mean and verified that the data satisfied assumptions of Gaussian distribution and homoscedasticity. These assumptions were violated in the accuracy data. Thus, we replaced the *t* test with a Mann–Whitney *U* test when comparing accuracy.

Results

Visuospatial attention does not influence implicit adaptation

To isolate implicit adaptation, we used task invariant, clamped feedback during a visuomotor adaptation task (Morehead et al., 2017). To manipulate visuospatial attention in Exp 1, we had participants perform a secondary visual discrimination task in which the stimulus for discrimination required the participant to orient spatial attention either toward or away from the feedback cursor. Specifically, an arrow was positioned within the reaching target, and, following the reach, the participant was required to report the orientation of the bar on the cued side (Fig. 1*a*). Because the bar was presented briefly (∼50 ms), we assumed that participants would shift their attention (and eyes) to the cued location. Mean accuracy on the secondary task was 79.2% in Exp 1a, indicating that the secondary task was demanding (Fig. 1*b*; Fig. S1). With this design, we asked if the magnitude of adaptation differed as a function of whether the clamped feedback appeared adjacent to the cued bar or distant from the cued bar.

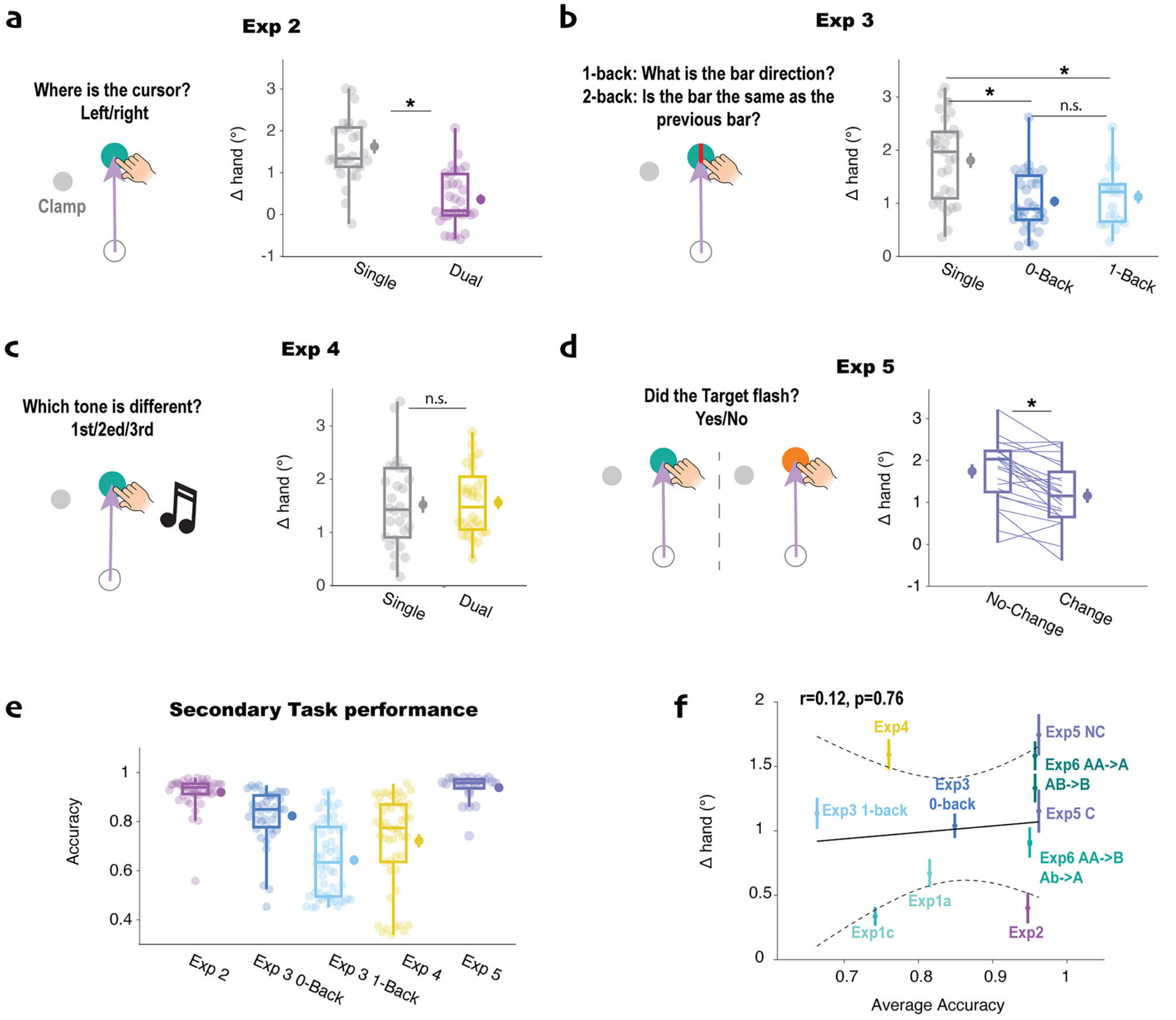

Figure 3. Implicit adaptation is not modulated by the availability of cognitive resources. ***a***, Exp 2, Adaptation is attenuated in a dual-task condition in which participants had to identify the position of the clamped cursor after completing the reach. ***b***, Exp 3, The bar was presented on the target, and participants either ignored the bar (single-task), reported the bar orientation on the current trial (zero-back, low-demand dual–task), or reported if the bar orientation matched that observed on the previous trial (one-back, high-demand dual–task). Adaptation was highest in the single-task condition, but the degree of attenuation did not differ between the low- and high-demand versions of the dual-task conditions. ***c***, Exp 4, An auditory pitch discrimination task was used for the secondary task with performance compared with a group instructed to ignore the tones. Adaptation was not attenuated in the dual-task condition. ***d***, Exp 5, Participants reported if the target color remained constant or briefly changed to red. Although the secondary task set was similar in conditions, adaptation was attenuated on change trials compared with no-change trials. ***e***, Accuracy on the secondary tasks of Exps 2–5. ***f***, Relationship between implicit adaptation and secondary task difficulty, with latter defined by secondary task accuracy. The black line indicates the best-fit linear model, and dashed lines indicate 95% confidence interval. This post hoc analysis provides further evidence that adaptation is not modulated by secondary task difficulty. $^*p < 0.001$; n.s., not significant.

As our assay of implicit adaptation, we measured the trial-by-trial change of hand angle (Δhand) driven by the clamped feedback. Participants showed significant trial-by-trial adaptation: Overall, the mean Δhand was of 0.77 ± 0.12° (mean ± SE) on trials in which the clamp appeared near the attended bar and 0.56 ± 0.16° on trials in which the clamp was opposite the attended bar (Fig. 1*c*). Importantly, the magnitude of adaptation did not differ between the two conditions ($t_{(34)} = 1.2$; $p = 0.24$; $d = 0.20$; bf10 = 0.35), suggesting that this process is not modulated by spatial attention. There was no consistent change in the hand angle after the no-feedback trials, confirming that the change in the hand angle after feedback trials is due to the clamped feedback and not the presence of a secondary task. Reaction time was consistent across all conditions (Fig. S2).

We confirmed this null result with a series of additional experiments (see Text S1 for details in Exp 1b–1f). First, we increased the eccentricity of the clamp and bar to 30° in Exp 1b, hypothesizing that this would increase the demands on reorienting attention. There was still no difference in the hand angle between the attended and unattended conditions ($t_{(34)} < 1.1$; $p = 0.80$; $d = 0.04$; bf10 = 0.19; Fig. 1*c*). Second, to address concerns that attention might be object specific (Logan, 1996; Roelfsema et al., 1998) and, thus, when directed to the bar, the feedback cursor falls outside the spotlight of spatial attention, we superimposed the bar on the cursor in Exp 1c. Again, there was no effect of attention ($t_{(57)} = 0.49$; $p = 0.62$; $d = 0.06$; bf10 = 0.16; Fig. 1*d*). Third, we presented symmetric feedback cursors in Exp 1d, a manipulation shown

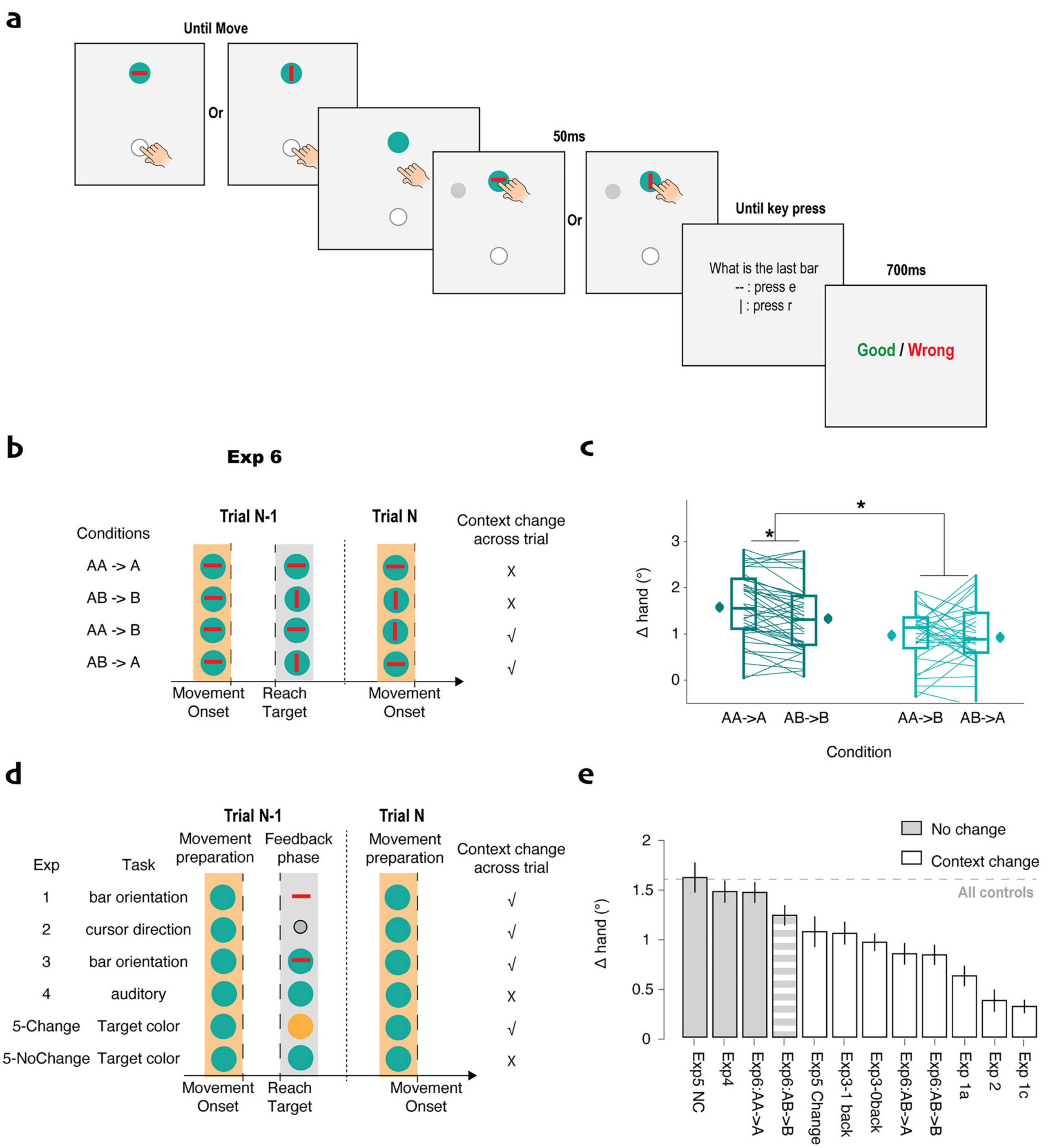

Figure 4. Implicit adaptation is attenuated when the attended stimulus changes between the feedback phase of trial $n-1$ and movement planning phase of trial *n*. ***a***, Exp 6, A bar, oriented horizontally or vertically, is presented on the target at the trial onset (movement preparation) and disappears at the movement onset. A second bar appears with the feedback cursor, either in the same or different orientation. The participant reports the orientation of the second bar. ***b***, The truth table showing how bar orientation at different phases determines whether the context is consistent or changes. We define a context change when the attended stimulus at the end of the trial $n-1$ is different than the attended stimulus at the start of trial *n*. ***c***, Adaptation was attenuated in the context-change group (AA→B and AB→A) compared with the no-change group (AA→A and AB→B). Moreover, the no-change group showed a within-participant effect with adaptation reduced in the AB→B condition compared with AA→A condition. ***d***, Summary of contextual change in the relevant dual-task conditions of Exps 1–6. ***e***, Δhand, rank ordered by magnitude of adaptation with shading to indicate conditions in which the context is unchanged. For the AB→B condition, while the attended stimuli were consistent at the end of trial $n-1$ and start of trial *n*, a context change may have resulted from the fact that the stimuli are different at the start of trials $n-1$ and *n*. The dotted line labeled "All controls" refers to the average of the single-task conditions. Error bars indicate standard error.

previously to result in no adaptation (Tsay et al., 2024). We obtained a similar null effect even when attention was directed to one of the cursors ($t_{(59)} = 0.72$; $p = 0.47$; $d = 0.09$; bf10 = 0.18; Fig. 1*e*). Lastly, we replicated Exp 1c and 1d, using a design in which the effects of adaptation accumulate over trials. We hypothesized this might amplify any potential effect of attention (Exp 1e and 1f). However, no effect of attention was observed (Fig. 2). In summary, across all experiments, we found no evidence that visuospatial attention modulates implicit adaptation.

Inclusion of a secondary task can influence implicit adaptation

Despite the absence of a modulatory effect of visuospatial attention on adaptation, the trial-by-trial change in the hand angle in Exp 1 was small (~0.5°) compared with that observed in previous experiments using the same platform but without a secondary task (1.5–2°; Tsay et al., 2021b; Wang and Ivry, 2023). This result suggests that the inclusion of a secondary task can influence adaptation. In the remaining experiments, we systematically assess this hypothesis, seeking to understand the factors by which a secondary task impacts implicit adaptation.

As a first step, we wanted to confirm that the attenuation in Exp 1 was not due to the inclusion of the extra visual stimuli (the bars), stimuli that might interfere with processing the cursor feedback. To this end, we used a simplified secondary task in Exp 2, one in which the display was limited to the target and clamped feedback cursor (Fig. 3*a*). For the dual-task condition, the participant was instructed to pay attention to the clamped feedback and report the cursor's location relative to the target (left or right). In the control, single-task condition, the participant was told to ignore the clamp. To match the motor demands, the participant was required to press a specified key after each movement. This also allowed us to roughly match the duration of each trial in the two conditions (Fig. S3).

A priori, one might expect that attending to the feedback cursor in the dual-task condition would increase adaptation. However, the opposite was found: Adaptation was attenuated in the dual-task condition compared with the single-task condition ($t_{(59)} = 6.2$; $p < 0.001$; $d = 1.6$; $\mathrm{bf10} = 1.8 \times 10^5$; Fig. 3*a*). For the latter, the trial-by-trial change in the hand angle was ~1.6°, a value similar to that observed in prior studies (Tsay et al., 2021b; Wang and Ivry, 2023). In contrast, the magnitude of adaptation dropped to ~0.5° in the dual-task condition. This result further confirms that paying attention to the feedback does not boost adaption. Rather, it appears that the inclusion of a secondary task can attenuate implicit adaptation. We considered the alternative hypothesis that the attenuation associated with the secondary task might be due a longer intertrial interval (ITI) given that adaptation decays rapidly with time (Smith and Bowen, 1980; Brudner et al., 2016). However, ITI did not differ between the single- and dual-task conditions (Fig. S3).

Implicit adaptation does not tax cognitive resources

Why might a secondary task attenuate adaptation? One possible explanation is that attenuation is the result of resource sharing between the primary reaching task and the secondary task. We performed three experiments to test this hypothesis; as shown below, the results consistently argue against the cognitive load hypothesis.

In Exp 3, we manipulated the demands on working memory. Specially, we compared three conditions in which we varied the processing demands associated with the secondary task. In the single-task condition, participants were instructed to ignore the red bar. In the low-demand condition, the participant indicated the orientation of the bar right after a movement (zero-back). In the high-demand condition, the participant reported if the orientation of the bar matched that shown on the previous trial (one-back task). The accuracy data confirmed our expectation that the one-back condition is more difficult and, presumably, more demanding on cognitive resources: Accuracy on the orientation task dropped to 67% in the high-demand condition compared with the 86% in the low-demand condition (Mann–Whitney *U* test, $z = 5.4$; $p < 0.001$; Fig. 3*e*).

Adaptation was lower in both of the dual-task conditions compared with the single-task condition (one-back, $t_{(49)} = 3.4$; $p = 0.001$; $d = 0.98$; $\mathrm{bf10} = 25.5$; zero-back, $t_{(62)} = 4.7$; $p < 0.001$; $d = 1.2$; $\mathrm{bf10} > 1{,}000$); consistent with the results of Exps 1 and 2, inclusion of a secondary task attenuated adaptation. However, the level of adaptation was similar for the high and low conditions despite the difference in difficulty (Fig. 3*b*; $t_{(51)} = -0.63$; $p = 0.53$; $d = -0.18$; $\mathrm{bf10} = 0.33$). Thus, the degree of attenuation does not seem to be related to the resource demands of the secondary task, a finding that is at odds with the hypothesis that adaptation is modulated by the availability of cognitive resources.

We next asked if the attenuating effect of a secondary task would also be observed if that task involved a different modality. In Exp 4, we used an auditory secondary task in which three tones were presented, with the pitch the same for two of the tones and differing by an octave for the third tone. Participants in the dual-task condition indicated the ordinal position of the oddball while participants in the single-task condition were instructed to ignore the auditory stimuli. The magnitude of adaptation was comparable in the two conditions ($t_{(54)} = 0.13$; $p = 0.89$; $d = 0.04$; $\mathrm{bf10} = 0.27$; Fig. 3*c*), providing further evidence against a general resource account. Moreover, adaptation was comparable in this experiment to that observed in in the single-task conditions of Exps 3 and 4.

In the third test of the resource hypothesis (Exp 5), we used a within-participant design, keeping the attentional demands constant while manipulating the visual display. We used a detection task in which, at the onset of the cursor feedback, the color of the target briefly changed from blue to red on 50% of the trials, whereas it remained blue on the other trials. After completing the reaching movement, the participant indicated if they had detected a color change. Given that the participants' task is the same for change and no-change trials, we would expect a similar adaptation response if the magnitude of adaptation is influenced by cognitive resources. However, we observed reduced adaptation following change trials compared with no-change trials ($t_{(21)} = 5.3$; $p < 0.001$; $d = 1.26$; $\mathrm{bf10} = 867$; Fig. 3*d*), with adaptation following no-change trials similar to that observed in the previous single-task conditions.

Considered as a package, the results of Exps 3–5 fail to support the hypothesis that implicit adaptation is modulated by the availability of cognitive resources. The magnitude of adaptation was not influenced by working memory load, nor did we observe attenuation of adaptation when the secondary task was in a different modality. As a post hoc analysis, we compared all of the relevant conditions from this paper and found no correlation between the difficulty of a secondary task and the rate of adaptation (Fig. 3*f*), providing further evidence that adaptation is not impacted by the availability of cognitive resources.

Attention influences adaptation by defining the context

In reviewing the conditions that produced attenuation of implicit adaptation, we recognized one consistent feature: The stimulus that was the focus of visual attention at the end of the trial $n - 1$ is different compared with the stimulus that is the focus of visual attention at the start of trial *n* (Fig. 4*d*). For example, each dual-task trial in Exp 1a–1c ends with a report of the orientation of a bar, whereas the bars are not part of the display at the start of the next trial. Another, more compelling example comes from Exp 2. Although the displays are identical on the dual- and single-task trials, the focus of attention shifts to the clamped cursor in the former, whereas it (at least as instructed) remains focused on the target in the latter. Whereas we find attenuation when there is a shift in the focus of attention, no attenuation is observed when the focus of visual attention is unchanged across trials. This distinction is apparent when considering the conditions of Exp 5. Attenuation is only observed when the target color had changed on trial $n-1$.

Why might this change in the focus of attention produce an attenuation of adaptation? We propose that this effect can be understood from the perspective of a contextual inference model (Haruno et al., 2003; Heald et al., 2022). We refer to context as a discrete latent variable that determines the contingencies between actions and sensory consequences. For example, kicking a ball on a day in which a strong wind is blowing might require adjusting the force and direction of the kick. In our experimental setup, the relationship between the hand and feedback cursor can define distinct contexts (veridical feedback or clamped feedback). Achieving the desired action goal requires a distinct motor policy for each of these contexts.

Classic models of motor learning propose that the sensorimotor system builds separate memories or internal models for different contexts (Haruno et al., 2003; Heald et al., 2021). The system updates and retrieves the model that is associated with the inferred context. To infer the current context, the system relies on contextual cues, the sensory and/or task-related information that helps distinguish one context from another. Visual stimuli, task configurations (such as start location), or even movement dynamics can serve as contextual cues (Howard et al., 2013, 2015).

From the results observed in the current study, we propose that the focus of attention can also serve as a contextual cue. When the focus of visual attention changes, adaptation is attenuated because there is limited transfer between contexts. For example, errors used to update a model of the environment with an oriented bar in trial $n-1$ may not generalize to a model of the environment without the bar in trial n. Following this logic, presenting the same bar during movement preparation in trials $n-1$ and n should mitigate the attenuation effect.

To test this hypothesis, we manipulated the consistency of the contextual cue in Exp 6 (Fig. 4*a*). A bar, oriented vertically or horizontally, appeared on the target at the start of the trial and disappeared at the movement onset. Another bar, with either the same or different orientation, appeared on the target concurrent with the clamp. After the reach, the participant reported the orientation of the second bar. With this design, we assume that the participants attended to both bars: The first one because they need to attend to the target to determine the reach direction and the second one because it is required by the secondary task.

When considered as contextual cues, the first bar defines the context for memory expression, while the second bar defines the context for memory updating (Fig. 4*b*). To test the contextual change hypotheses, we employed a between-participant design in Exp 6. For one group of participants, the orientation of the second bar (presented with the feedback cursor) on trial $n-1$ was the same as the orientation of the bar at the target onset on trial n (AA→A and AB→B). Here we assume the context does not change since the retrieved internal model is the same as the one that was just updated. In contrast, for the second group, the orientation at the target onset on trial n differs from that presented at the end of trial $n-1$ (AA→B and AB→A); for this group the context has changed as the retrieved internal model is not identical to the one that was just updated. Based on prior work showing that generalization of adaptation is limited when the context changes (Howard et al., 2013, 2015), we predicted that the context-change group would show reduced adaptation.

The results of Exp 6 are consistent with the hypothesis that attentional modulation of implicit adaptation is mediated by contextual variation. A mixed ANOVA revealed that adaptation is significantly reduced when the bars change orientation at the onset of trial n ($F_{(146)} = 15.8$; $p < 0.001$; Fig. 4*c*). Post hoc t tests showed that adaptation in both the AA→A and AB→B conditions was greater than in the AA→B and AB→A conditions, respectively (t's > 2.6; $ps_{\mathrm{FDR}} < 0.016$; ds > 0.61; bf10s > 4.0). Interestingly, we also observed a slight decrease in adaptation in the AB→B condition compared with the AA→A condition ($t_{(42)} = 4.1$; $p_{\mathrm{FDR}} < 0.001$; $d = 0.62$; bf10 = 129). We hypothesize that the difference between the AB→B and AA→A conditions might also reflect a context change, with the context for memory updating determined not only by the stimulus attended during the feedback phase but also by the stimulus attended during movement preparation. That is, there is a context change in the AB→B condition given that the bar orientation at the target onset differs between trials $n-1$ and n.

These results motivated us to review the relevant dual-task conditions across experiments in terms of the contextual change hypothesis (Fig. 4*e*). Notably, in all conditions in which the context remains consistent, the magnitude of adaptation is similar and falls within the mean value of adaptation observed in single-task conditions. In contrast, attenuation is observed whenever there is a change in context cues. Interestingly, the dual-task conditions in Exps 1 and 2 show the strongest attenuation. These are the two conditions in which the spatial focus of attention (and presumably fixation) changed from the end of trial $n-1$ to the start of trial n. Such spatial shifts may define a more substantial context change.

Discussion

The current study addresses whether and how visual attention modulates implicit sensorimotor adaptation. Taken as a package, the results reveal three key findings. First, implicit adaption was not directly modulated by the focus of visuospatial attention: The rate and extent of implicit adaptation were unaffected by whether participants paid attention to the feedback cursor. Second, implicit adaptation does not require attentional resources as variation in the difficulty of a secondary task had no influence on adaptation across the set of experiments. Third, attention can modulate adaptation in an indirect manner. Specifically, stimuli that are the focus of attention serve as cues to help define the learning context, and this context constrains how the sensorimotor map is updated and expressed. When the attended stimuli change across trials, learning is attenuated due to imperfect generalization between nonidentical contexts.

Attention defines the relevant contextual cue for sensorimotor memory

The relevance of context-dependent learning has been explored in studies of sensorimotor adaptation, perhaps most dramatically in studies showing limitations in generalization (Krakauer et al., 2006). Initially, the limits on spatial generalization were described in terms of tuning functions (Krakauer et al., 1999). However, subsequent studies showed that generalization for movements in the same direction was also limited if the action was performed with different tools (Kluzik et al., 2008) or even if the target shape changed across trials (Poh et al., 2021). These observations motivated the idea that the sensorimotor system develops distinct internal models for different contexts and that generalization is dependent on the degree of overlap between contexts. Thus, even when the trials are interleaved, participants can even learn to respond to perturbations in opposite directions if the movements are associated with distinct contextual cues (Howard et al., 2015).

However, the criteria that define the contextual cues for sensorimotor learning remain unclear. The seminal work of Howard and colleagues highlighted how spatial and/or dynamic cues were more important for defining the context for sensorimotor adaptation compared with simple, static cues such as color (Howard et al., 2013, 2015). Subsequent studies have shown that abstract features such as decision uncertainty can serve as contextual cues (Tsay et al., 2021a). Most relevant to the current study is the work of Song and colleagues, showing that attentional diversion can also be a context for adaptation (Song and Bédard, 2015; Im et al., 2016). In particular, generalization was greater when participants continued to do a secondary task compared with a condition in which they switched to a single-task condition (Song and Bédard, 2015; Liddy and Song, 2022).

While there is a substantial empirical literature showing the features that can (and cannot) serve as contextual cues, the underlying principles determining their effectiveness remain unclear. The results from the current study help define what constitutes an effective contextual cue for implicit adaptation. Taken as a whole, the results from our eight experiments suggest that for a visual cue to effectively define a unique context, that cue must be attended to by participants either while they are preparing for the movement (memory retrieval) or receiving feedback about the movement (memory updating). Crucially, the attended cue need not be part of the motor task to define the context for adaptation. As shown in many of our experiments, adaptation was attenuated when the stimulus for the secondary discrimination task was not relevant for the reaching movement (e.g., the target or feedback cursor). Conversely, a visual cue that is unattended failed to influence adaptation, presumably because such task-irrelevant cues are not part of the context.

Our hypothesis that attention has an indirect effect on adaptation by shaping the learning context provides a fresh perspective when considering previous findings on contextual cues. A large number of studies have shown how our ability to learn interleaved perturbations varies in a dramatic way as a function of the cues used to define those perturbations (Howard et al., 2013, 2015). We would argue that the varying effectiveness of different stimuli reflects their capacity to engage attention. Similarly, abstract properties such as cognitive demands or task uncertainty can serve as effective contextual cues because they are critical features of the secondary task and, thus, a target of attention (Song and Bédard, 2015; Ogasa et al., 2024).

One puzzle here is the absence of attenuation in Exp 4 where we used auditory stimuli for the secondary task. Here we failed to observe a difference between the dual- and single-task conditions event though the auditory tones had to be attended to in the former. It may be that the modality separation between the primary (clamp) and secondary (tone) stimuli precluded the tones from defining a context for sensorimotor adaptation. However, Avraham et al. (2022) found that adaptation was equally robust in response to visual and auditory cues that were used as the imperative signal for a visual reach. We note that, in the present work, the auditory cue served as the imperative signal for the secondary perceptual discrimination task rather than for the primary reaching task.

Sensorimotor adaptation is automatic and not dependent on attentional resources

While we have shown how attention can modulate adaptation in an indirect manner by defining the learning context, our results also underscore the robustness of the implicit sensorimotor learning system. Previous research has shown that this implicit learning process operates in an obligatory manner; it cannot be suppressed even when the "error signal" is irrelevant to the task or when the operation of implicit adaptation actually degrades task performance (Mazzoni and Krakauer, 2006; Morehead et al., 2017). However, the fact that the process is obligatory does not preclude the possibility that it could be modulated by attention. For example, paying attention to the feedback might strengthen the error signal and enhance adaptation (Tsay et al., 2024).

Strikingly, our results indicate that implicit adaptation is unaffected by the focus of visuospatial attention. The rate and magnitude of adaptation was indistinguishable between conditions in which attention was focused in the vicinity of the feedback cursor compared with when attention was directed to the opposite side of the target, even when this distance spanned 60°. Moreover, we failed to observe an effect on implicit adaptation when the clamped cursor itself was the secondary stimulus compared with when participants were told to ignore this stimulus (Exp 2).

The results also indicate that implicit adaptation does not draw on attentional resources. While the attenuated adaptation in the dual-task conditions of Exp 2 would suggest an effect of attentional load, the context-change hypothesis offers a more parsimonious account. Indeed, Exps 3–6 provide multiple lines of evidence suggesting that manipulations of attentional resources do not impact implicit adaptation. First, there was no difference in the learning rates between the zero-back and one-back conditions of Exp 3. Second, performing an auditory secondary task in Exp 4 did not influence adaptation. Third, there was no attenuation in the dual-task conditions of Exps 5 and 6 in which the context did not change. Fourth, across the experiments, task difficulty did not correlate with the magnitude of adaptation. Collectively, these findings suggest that implicit adaptation is not impacted by the availability of attentional resources.

We also considered whether attentional demands specific to visual processing might influence implicit adaptation. For instance, a change in the visual stimulus during a trial could require extra visual processing and interfere with adaptation-related processes like processing the cursor feedback or memory updating. However, the data do not support this. First, the AA→B condition in Exp 6 involves no stimulus change, yet adaptation was reduced. Second, while the stimulus change in the first trial in the AB→B condition should increase the demands on visual processing, adaptation was higher on these trials compared with AA→B trials. Third, the visual processing demands appear similar in Exp 2 across the single- and dual-task conditions as adaptation in both requires processing the relative position of the cursor relative to the target. Nonetheless, adaptation was attenuated in the dual-task condition.

Why is the implicit sensorimotor system not modulated by attention? One possibility is that the system encodes the error in an all-or-nothing manner. As such, the computation of the sensory prediction error may require only superficial processing of the visual feedback to reach maximal reliability. This idea is supported by the observation that the magnitude of the error correction is insensitive to the error size over a large range (10–90°;

Kim et al., 2018) and signal clarity/salience as long as the direction of the error can be reliably computed (Tsay et al., 2021a). Moreover, the cerebellum is a key structure for implicit sensorimotor adaptation (Raymond and Lisberger, 1998; Shadmehr and Krakauer, 2008). The robustness of implicit adaptation may also reflect some degree of modularity between the cerebellum and cortex. A separation between systems involved in action selection and movement implementation may enable the implicit adaptation to keep the sensorimotor system precisely calibrated in a resource-free manner, freeing up attention to support the more flexible components of our mental world.

Data Availability

The data and code supporting this work are available at https://github.com/shion707/Attention-Implicit-Adaptation.

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