On the money and right on target: How robust are reward and task success effects on implicit motor adaptation?

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CONFLICT OF INTEREST

The authors declare no competing financial interests.

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ABSTRACT

We learn to improve our motor skills using different forms of feedback: sensory-prediction error, task success, and reward/punishment. While implicit motor adaptation is driven by sensory-prediction errors, recent work has shown that task success modulates this process. Task success is often confounded with reward, so we sought to determine if the effects of these two signals on adaptation can be dissociated. To address this question, we conducted five experiments that isolated implicit learning using error-clamp visuomotor reach adaptation paradigms. Task success was manipulated by changing the size and position of the target relative to the cursor providing visual feedback, and reward expectation was established using monetary cues and auditory feedback. We found that neither monetary cues nor auditory feedback affected implicit adaptation, suggesting that task success influences implicit adaptation via mechanisms distinct from conventional reward-related processes. Additionally, we found that changes in target size, which caused the target to either exclude or fully envelop the cursor, only affected implicit adaptation for a narrow range of error sizes, while jumping the target to overlap with the cursor more reliably and robustly affected implicit adaptation. Taken together, our data indicate that, while task success exerts a small effect on implicit adaptation, these effects are susceptible to methodological variations and unlikely to be mediated by reward.

KEYWORDS

Sensorimotor adaptation, motor learning, reinforcement

NEW & NOTEWORTHY

We are motivated to perform well and earn rewards, but do rewards help maintain motor skill calibration? Here, we observed that implicit motor adaptation is not sensitive to abstract signals of reward, such as money or auditory cues related to performance, although adaptation was influenced by visual signals of task success like hitting a target. These data suggest that the implicit motor system may be primarily concerned with performance metrics rather than rewards.

INTRODUCTION

There are multiple facets of good performance. As an example, consider a tennis serve. When the ball lands in the service box, we meet the minimum requirements for making a successful serve, and we experience what the motor learning literature refers to as "task success." We achieve an element of sensory prediction accuracy if we manage to place the ball in exactly the location to which we were aiming. Finally, if our opponent cannot return the ball, we earn a point and a reward by accomplishing one of the game's higher-level objectives. Reward drives changes in explicit movement planning, while errors in sensory prediction drive implicit motor adaptation, which refines our movements beneath the level of conscious awareness (Holland et al. 2018; Wolpert et al. 1998).

Recent work has indicated that task success can suppress implicit adaptation, and it has been proposed that these effects are mediated by the intrinsic reward associated with task success (Kim et al. 2019; Leow et al. 2018; Tsay et al. 2022). However, task success is a feedback signal inherent to the execution of any motor action, and it merely represents whether the movement met the minimum criterion for being considered successful. Thus, although task success and reward often coincide, they are dissociable. For example, a tennis serve may successfully land in the service box, but our opponent may return the ball and a point may not be won. By extension, task success signals may be processed in circuits distinct from those that process reward, and implicit adaptation may be sensitive to task success signals without exhibiting sensitivity to reward.

In this report, we set out to address whether task success affects implicit adaptation via a reward associated with successful movements or if this effect is reward-insensitive. We reasoned that, if task success acts via reward, greater reward should suppress implicit adaptation, and vice versa. While a substantial body of literature has shown effects of reward on motor learning in general (Cashaback et al. 2017; Codol et al. 2023; Galea et al. 2015; Hamel et al. 2018; van der Kooij et al. 2018; Nikooyan and Ahmed 2015), little work has directly tested the effects of reward on the implicit process. Thus, we employed the recently-developed error-clamp technique for isolating implicit motor adaptation during all of the studies described in this manuscript (Morehead et al. 2017). Our experiments also led us to assess the robustness of the effects of task success on implicit adaptation.

Two distinct kinds of task success feedback manipulations have been reported to suppress implicit learning during visuomotor reach adaptation (VMR) tasks: 1) Target Jump manipulations and 2) Target Size manipulations. During a VMR task, participants control a cursor by moving their arm, and their goal is to reach to a target. When the position of the cursor is perturbed, causing it to both travel to an unintended location (a sensory prediction error, SPE) and land off-target (task success errors, TSE), motor learning proceeds to recalibrate the system and correct for these errors. To control task success, Target Jumps that shift the target partway through a reach such that final target and cursor locations are overlapping eliminate TSE while preserving SPE (Leow et al. 2018, 2020; Tsay et al. 2022). An alternate approach manipulates Target Size rather than target position: either a large target is presented that completely encompasses the cursor at the end of its perturbed trajectory (SPE + null TSE), or a small target that partially excludes the cursor (SPE + TSE) is presented (Kim et al. 2019). Participants exhibited lower levels of adaptation when they experienced task success in response to both Target Jumps or Target Size manipulations.

As Target Size manipulations employ constant target stimuli throughout a single trial and are less likely to drive dynamic attentional shifts during a reach, our initial experiments used this approach. Thus, Experiments 1-3 combined Target Size manipulations with extrinsic reinforcers including money and pleasant auditory feedback in an effort to assess whether reward and task success cues exert similar effects on implicit learning. However, after encountering difficulties replicating effects of Target Size, we transitioned to the Target Jump approach to confirm that task success manipulations in general influence implicit adaptation (Experiment 4). Finally, in Experiment 5, we examined the effects of task success across a wide range of SPE magnitudes to assess the robustness of the two task success manipulations and to assess whether there is an inverse relationship between reward efficacy and SPE magnitude (Cashaback et al. 2017).

MATERIALS AND METHODS

Participants. Participants (*n* = 268, 168 female, 19.87 ± 1.66 years of age ranging from 18 to 29 years, 254 right-handed and 12 ambidextrous as determined by the Edinburgh Handedness Inventory [Oldfield, 1941]) were recruited from the Princeton University community. All participants provided informed, written consent in accordance with procedures approved by the Princeton University Institutional Review Board. Participants received either course credit or a $12 honorarium as compensation for their time. Participants in Experiment 1 received an additional $3, in line with monetary rewards promised as a part of the task design. A power analysis (GPower V3.1) of Kim and colleagues' (2019) Experiment 3 indicated that 22 subjects per group would be required for 95% statistical power given their reported effect size, so we opted to collect 24 participants per group in Experiments 2 and 3. A power analysis of the results of Experiment 4 reported here indicated that 40 participants would be required to obtain sufficient statistical power to observe an effect of jumping the target provided the number of pre-planned post-hoc comparisons, so we collected data from 42 participants for Experiment 5. Sample sizes for experiments 1 and 4 (*n* = 16/group) were not determined by power analysis, but are greater than sample sizes in other studies in the literature investigating the effects of reward and task success on implicit adaptation in the laboratory (Kim et al. 2019; Tsay et al. 2022).

Apparatus. Participants performed a center-out reaching task while vision of the hand was obscured by an LCD monitor (60 Hz, 17-in., Planar Systems, Hillsboro, OR) mounted 27 cm above a digitizing tablet (125 Hz, Wacom Intuos Pro L, Wacom, Vancouver, WA). Participants controlled a visually-displayed cursor by moving a stylus, which was embedded in an air hockey paddle, with their right hand (**Fig. 1A**). We opted to use the air hockey paddle system as opposed to the stylus alone 1) to encourage participants to make arm movements about the shoulder and elbow joints instead of the joints of the wrist and fingers and 2) to replicate the experimental conditions of Kim et al. (2019) as closely as possible (personal communication). Experimental software was programmed in Matlab R2013a using the Psychtoolbox extension V3.0, and was run on a Dell OptiPlex 7040 computer (Dell, Round Rock, TX) with a Windows 7 operating system (Microsoft Co., Redmond, WA). All stimuli were presented on a black background that filled the display. Experiments were conducted with the room lights extinguished to limit peripheral vision of the arm and to maximize stimulus visibility.

Cursor feedback. A visually-displayed cursor (filled white circle, 1.5 mm diameter in Experiments 1 and 5, 3.5 mm diameter in Experiments 2-4) provided movement-related feedback (FB). During baseline and washout trials, the cursor either faithfully showed participants' hand locations throughout the trial (FB trials) or was not displayed (no-FB trials). On "error-clamp" trials, the angle of the cursor was fixed off-target and participants could only control the radial distance of the cursor (Morehead et al. 2017; **Fig. 1B**). In combination with instructions to ignore the error-clamp FB and reach straight for the target, this manipulation reliably isolates implicit adaptation and minimizes explicit re-aiming (Kim et al. 2018; Morehead et al. 2017).

Center-out reaching task. To initiate a trial, participants positioned the hand in a central start location (6 mm diameter) using a guide circle that limited cursor feedback between trials (radius = distance between the hand and the starting location). When the hand was within 1 cm of the start location, the guide circle disappeared and veridical cursor FB was displayed. After the hand was in the starting location for 500 ms, a blue (RGB blue) target appeared 8 cm away. Participants were instructed to quickly slice through the center of the target without stopping before returning to the start location to initiate the next trial. When provided, cursor FB at the target distance was sustained for 50 ms. If the target-directed movement duration exceeded 600 ms, “Too Slow” was displayed in red on the screen and played through the computer speakers after the trial. When the target was presented at multiple locations within an experiment, trials were presented in “cycles,” such that all targets were experienced at all possible locations before being repeated.

Procedure.

Experiment 1. Experiment 1 aimed to test the hypothesis that reward modulates implicit adaptation. Thus, we presented monetary cues, either a penny or a dollar, to explicitly modulate the reward value of hitting the target. To assess whether any effects of reward on implicit adaptation were mediated by a modulation of that process or by learning in a separate process, we leveraged the transfer design of Experiment 3 in Kim et al. (2019). In their design, the task success condition was switched halfway through the experiment, such that if participants initially received task success (or failure) feedback, the target size changed to to deliver task failure (or success) feedback in the next block of the experiment. A reversal in the asymptotes was interpreted as evidence that task success modulated implicit adaptation directly rather than through a parallel process (Kim et al. 2019). Because our experiment focused on the effects of reward rather than task success, we changed the amount of reward available halfway through the training block rather than changing the Target Size condition, to test whether changes in monetary reward would similarly elicit changes in asymptotic motor performance.

Potential reward was signaled by monetary cues presented before error-clamp trial onset. An image of either a penny (¢) or a dollar ($) was displayed at the starting location during the 500-ms center hold period before the target was illuminated, and participants were told they could earn the amount of money displayed if their hand sliced through the center of the target.

Targets could appear in 4 possible locations (45°, 135°, 225°, 315°), and the target appeared at each possible location during each cycle. The session proceeded as follows: 10 cycles without cursor FB (No FB Baseline), 10 cycles with veridical cursor FB (FB Baseline), 80 cycles with 1.75° error-clamped FB and the first level of reward available (Reward Block A), 80 cycles with 1.75° error-clamped FB and the second level of reward available (Reward Block B), 10 cycles without cursor feedback (No FB Washout), and 10 cycles with veridical FB (FB Washout). The direction (clockwise or counterclockwise) of the error-clamp was counterbalanced across participants. Before Reward Block A, participants were briefed on the nature of the error-clamp manipulation and instructed to ignore the cursor feedback. We also instructed participants to do their best to reach directly for the center of the target, as they would earn the displayed monetary reward on randomly-selected trials if their hand (not the cursor) passed through the center of the target. They were informed that either a penny or a dollar would be available, and that they would see both rewards during the experiment although their total payout would only be revealed at the end of the study. All participants received $3 at the end of the experiment, and were debriefed that their monetary compensation had no relation to their performance.

Participants (n = 64) were randomly assigned to one of four groups according to a 2 x 2 design in which we crossed the two factors of interest: potential reward and task success. As the amount of reward available changed halfway through the error-clamp block, participants were assigned to either the "¢ to $" condition (*i.e.*, ¢ available for error-clamp block A and $ available for error-clamp block B) or the "$ to ¢" condition. Task success was controlled during the error-clamp block by controlling the target size. Participants assigned to the "Straddle" condition saw a small target (6 mm diameter) so that the cursor straddled the target (50% on and 50% off-target) during the error-clamp blocks, simulating task failure. Participants assigned to the "Hit" condition saw the larger target (16 mm diameter) so that the cursor landed completely within the target during the error-clamp blocks, simulating task success.

Experiment 2. Experiment 2 aimed to faithfully replicate Experiment 1 of Kim et al. (2019), which demonstrated attenuation of implicit motor learning when participants saw cursor FB that hit the target.

The session proceeded as follows: 5 cycles of no-FB baseline, 10 cycles of veridical-FB baseline, a 3-trial 45° clamp tutorial, 80 cycles of 3.5°-error-clamped FB (clamp direction counterbalanced across subjects), 5 cycles of no-FB washout, and finally 10 cycles of veridical-FB washout. During each cycle, targets appeared once in each of 8 possible locations: 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. The 3-trial clamp tutorial phase aimed to inform participants about the nature of the clamp through practice. On each trial, the target appeared straight ahead (90°), and participants were instructed to reach in different directions away from the target to demonstrate the lack of contingency between reach and cursor FB directions (Tutorial trial 1: straight to the right, trial 2: straight left, trial 3: straight back/towards the body). Following the tutorial, the experimenter instructed participants to ignore the cursor and try to slice through the target location with their hand.

Participants (*n* = 48) were divided into two groups. One group saw a larger, 16 mm diameter target, such that, during clamp trials, the cursor landed completely within the target ("Hit" group). The other group saw a smaller, 6 mm diameter target that excluded the error-clamped cursor ("Miss" group; **Fig. 1C**).

Experiment 3. Experiment 3 was designed to standardize participants' perceptions of task error, regardless of visual FB, by employing tones to indicate success or failure. This experiment proceeded largely as described for Experiment 2, with the exceptions described below.

In addition to visual FB, participants (*n* = 96) received auditory FB at the end of each reach. A pleasant dinging sound played at the end of the trial when the cursor (or hand, during no-FB blocks) landed within a certain angular distance of the center of the target. Otherwise, an unpleasant knocking sound was played. Participants (*n* = 96, 24/group) were divided into 4 groups. The larger 16 mm diameter target was displayed to two groups ("Hit" groups) and the smaller 6 mm diameter target was displayed to the other two groups ("Miss" groups). Hit and Miss groups were further divided into groups with a stricter distance threshold for playing the pleasant dinging sound (6mm, "Strict") or a more lenient distance threshold (16mm, "Lenient"), such that participants in the Strict groups heard the unpleasant sound at the end of each trial during the error-clamp block while participants in the Lenient groups heard the pleasant sound at the end of each error-clamp trial.

During the 3-trial, 45°-error clamp tutorial, in addition to instructions related to the cursor feedback, participants were instructed that the sounds would no longer correspond to their actual performance, and instead corresponded to the distance of the cursor relative to the center of the target. Thus, they had no control over both the trajectory of the clamped cursor and the sounds that would play at the end of the trial. When participants reached the washout phases, they were informed that the auditory and cursor feedback once again reflected their performance.

Experiment 4. Experiment 4 was designed to test whether an alternative method of manipulating task success – the target jump – would effectively influence implicit adaptation. Since these effects have been reported previously, we modeled our study after experiments described by Tsay et al. (2022).

Participants (n = 18) reached to a single target location (90° [straight ahead]) throughout the study. First, they performed 100 baseline trials during which they received veridical FB. Then, we explained the nature of the error-clamp manipulation to participants and walked them through 3 demonstration trials, as described for Experiments 2 (above). Subsequently, they were exposed to 800 trials with 4° error-clamped FB, and the direction of the error-clamp was varied randomly on each trial to maintain mean levels of adaptation around zero during the study. Then, on each trial, participants saw one of four different possible target jump contingencies: No Jump, Jump-To, Jump-Away, and Jump-in-Place. As a control, on "No Jump" trials, the target simply appeared and underwent no changes during the trial. To test the effects of eliminating task error on implicit adaptation, "Jump-To" trials were included where the target jumped 4° so that the error-clamped cursor FB landed directly on the center of the target. To test the effects of increasing task error on implicit adaptation, on "Jump-Away" trials the target jumped 4° in the direction opposite the error clamp so that the center of the target was 8° from the center of the error-clamped FB. Finally, "Jump-in-Place" trials on which the target was extinguished for 1 frame before being re-illuminated in the same location were included to control for attentional effects of the target disappearing from its original location. We opted to hide the target for a single frame (12 ms, in our case), as this was the "duration" specified by an earlier report utilizing the jump-in-place manipulation (Tsay et al. 2022). This duration also produced a noticeable change in the visual display that approximates the experience of noticing the displacement of the target in the target jump conditions. All target manipulations were implemented when the hand passed 1/6 of the distance to the target on each trial. Single-trial learning was quantified as the change in reach angle between two subsequent trials.

Experiment 5. Experiment 5 was designed to test whether the effects of task success on implicit adaptation depend on error magnitude and task success manipulation. Thus, we employed the Target Jump and Target Size manipulations, similar to what was described for Experiments 1-4, and measured single-trial learning as described for Experiment 4.

As in Experiment 4, all targets appeared straight ahead (90°), and the study began with a 100-trial baseline period with veridical cursor FB followed by a 3-trial error-clamp tutorial phase. Then, an 865-trial error-clamp phase began. During this phase, participants encountered error-clamp magnitudes of 1.75°, 3.5°, 5.25°, 7°, 8.75°, and 10.5° (clockwise and counterclockwise). On each trial, they also experienced one of three levels of task success: Miss, Hit, and Target Jump-To (Jump-To). On Hit trials, the target was 31 mm in diameter and completely encompassed the cursor on the 10.5° error-clamp trials. On Miss trials and Jump-To trials, the target was 4.5 mm in diameter and completely excluded the cursor on the 1.75° error-clamp trials. During Jump-To trials, the target shifted ⅙ of the way through the participant's reach such that the cursor and target were concentric at the end of the trial.

Statistical Analysis.

Raw data were preprocessed in MATLAB 2020a before being further processed and undergoing statistical analysis in R (RStudio, 1.3.959; RStudio, PBC, Boston, MA, R, 4.1.1). Because differences in approaches to data analysis may cause follow-up studies to fail to replicate initial reports, we analyzed the data following the approaches used in the studies we intended to replicate. Thus, for experiments solely dealing with Target Size task success manipulations (Experiments 1-3), we employed the approach described by Kim et al. (2019) and measured reach angle at the hand position at the time of maximum velocity on each trial. For experiments including Target Jump manipulations (Experiments 4-5), we used the approach of Tsay and colleagues (2022) and measured reach angle as the hand position at the time that the hand passed the center of the target. Two criteria were used to exclude trials from further analysis, based on the practices in the previous reports. First, trials on which the reach angle deviated from the target angle by more than 90° were excluded. Second, trials on which the reach angle deviated from the running average (5-trial window) by more than 3 standard deviations were also excluded. Across this report, <1% of trials were excluded (Experiment 1: 0.8%, Experiment 2: 1%, Experiment 3: 0.6%, Experiment 4: 0.5%, Experiment 5: 1%) via these criteria. For Experiments 4 and 5, we also excluded trials on which participants reached toward the only/expected target location (straight ahead) before the target appeared. This led us to exclude an additional 3.7% of trials from Experient 4 and 4.4% of trials from Experiment 5. For Experiments 1-3, veridical feedback baseline biases for each participant at each target were then computed and subtracted from the reach angles.

For Experiments 1-3, reach angles were subsequently binned by cycle (see *Procedure* above). Early learning rates were calculated as the estimated average change in hand angle over the first five cycles of the clamp block. To stably estimate the level of adaptation at cycle 5, cycles 3-7 were averaged. Asymptotic adaptation was estimated as the average reach angle over the last ten cycles of the clamp phase. Retention ratios were quantified as the ratio of reach angle in the final cycle of the no-FB washout phase to the reach angle in the final cycle of the preceding error-clamp phase. In the interest of replication, these definitions of learning rate, asymptotic performance, and retention were chosen for consistency with the report from Kim and colleagues (2019) (Protzko and Schooler 2017).

In Experiments 4 and 5, single-trial learning was quantified as the difference in reach angle between subsequent trials. Individual participants' performance within each trial type was averaged within clamp direction, and then these mean values were averaged. Finally, performance within trial type was compared across participants.

When comparisons were only made between two conditions for an experiment, we used Student's t-tests (paired or unpaired, as was appropriate the sampling conditions). When comparisons were made between three or more conditions, we used a two-way ANOVA (repeated measures ANOVA was applied when appropriate for the sampling conditions). If main effects or interactions were found to be statistically significant in the ANOVA, we followed up with appropriate post-hoc comparisons. Type-I errors were limited by adjusting p-values to control the false-discovery rate.

RESULTS

Experiment 1: Do monetary reward cues affect implicit motor learning?

Prior studies using reaching tasks have shown that performance-irrelevant but success-related cues attenuate visuomotor adaptation during reaching tasks (Kim et al. 2019; Leow et al. 2018). Kim and colleagues (2019) argued that this manipulation influenced adaptation via intrinsic reward. As this prior work manipulated visual feedback (FB) related to the relative locations of the cursor and target, we sought to build upon these findings by testing whether reward cues can modulate the effect of task success or whether the implicit motor system is only sensitive to stimuli directly pertinent to movement feedback. To this end, we presented monetary cues signaling the potential reward for successful reaches and tested for effects on implicit motor adaptation. Experiment 1 used a 2x2 crossed design, with levels of the first factor corresponding to different amounts of monetary reward (Penny [¢] or Dollar [$]) and levels of the second factor corresponding to different degrees of task success implemented via a Target Size manipulation. To assess whether the monetary reward directly or indirectly modulated implicit adaptation in the fashion of Kim et al., we switched the amount of reward participants could earn halfway through the training block.

Participants (n = 64, 16 per group) performed a center-out reaching task while vision of the arm was occluded by a planar monitor (**Fig. 1A**). To isolate implicit adaptation during the training blocks, we displayed error-clamped cursor FB: the cursor followed a trajectory 1.75° off-target regardless of the executed movement direction, enforcing a consistent sensory prediction error (**Fig. 1B-C**, Morehead et al. 2017). In order to mitigate any explicit re-aiming in response to cursor FB, we fully briefed participants about the error-clamp, instructed them to ignore the cursor FB, and told them that they had a chance to earn money if their hand (not the cursor) sliced through the center of the target. Immediately before each trial, an image of the money that could be won (a penny or a dollar) briefly appeared at the starting location (**Fig. 1D**). Depending on their group assignments, participants either reached for a large target that encompassed the error-clamped cursor FB (Hit) or for a small target that partially excluded the error-clamped cursor FB (Straddle; **Fig. 1C**).

Regardless of whether monetary rewards influence implicit adaptation, we expected to replicate the effects reported by Kim et al. (2019) and observe a suppressive effect of hitting the target on implicit adaptation. If monetary cues enhance participants' experiences of task success via the same reward processing system as Hit or Straddle FB, we would have expected a significant suppression of adaptation among participants in the $ condition, as the opportunity to earn $1 ought to be more appetitive than the opportunity to earn 1¢.

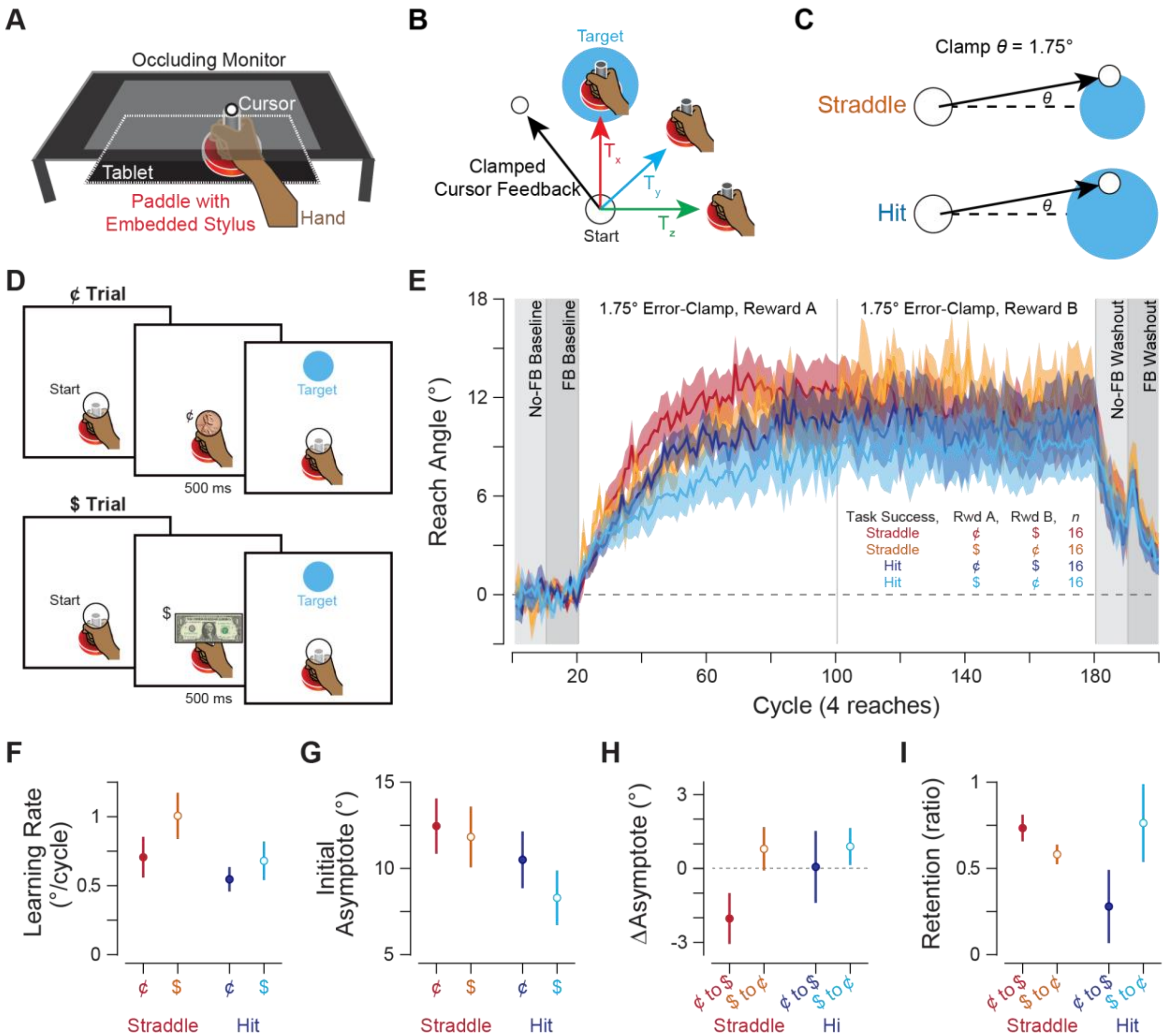

Figure 1. Effects of monetary cues and task success FB on implicit adaptation. (**A**) Experimental apparatus. Participants held a stylus and made reaching movements atop a digitizing tablet. Vision of the arm was occluded by a computer monitor that also displayed task FB. (**B**) Error-clamped cursor FB. During an error-clamp task, the cursor (white) travels along a predetermined trajectory (Clamped Cursor Feedback) relative to the target (blue) regardless of the reach trajectory (T_x, T_y, and T_z). (**C**) Error-clamped visual FB displayed to participants in the Straddle (orange, top) and Hit (blue, bottom) groups. (**D**) Monetary cues were displayed at trial onset. Either a penny (top) or dollar (bottom) was displayed while participants held their hand in the start location before target illumination. (**E**) Learning curves during Experiment 1. Inset table describes which monetary rewards were offered for each block of adaptation. (**F**) Learning rates during the first 5 training blocks of Experiment 1. (**G**) Asymptotic learning at the end of the Reward A training phase in Experiment 1. (**H**) Change in asymptote between the Reward A and B phases in Experiment 1. (**I**) Retention ratios in Experiment 1, with retention ratio defined as the proportion of the adaptation memory observed in the last cycle of no-FB washout relative to the last cycle of training.

Participants showed robust adaptation in response to the error-clamp phases (**Fig. 1D**). However, neither task success nor monetary cues statistically significantly affected participants' early learning rates, asymptotic adaptation, changes in performance with change in monetary cue, or retention during washout (**Fig. 1F-I**, see **Table 1** for details of statistical tests). Nonetheless, effects of Target Size-induced task success on learning rate (two-way between-subjects ANOVA, $F(1,60) = 3.06$, $p = 0.08$) and asymptotic adaptation ($F(1,60) = 2.76$, $p = 0.1$) trended towards significance. We also observed trends towards effects of changing the monetary cue on asymptotic performance ($F(1,60) = 2.94$, $p = 0.09$) and the interaction between Target Size and monetary cue on retention ($F(1,60) = 3.85$, $p = 0.054$). Although trend levels of significance provide ambiguous evidence for and against an effect of task success cues on implicit adaptation, the lack of robust reward sensitivity suggests that any influence of task outcome on implicit motor learning is not strongly driven by participant expectations about the potential reward associated with task success.

Considering that a strong effect of task success in this paradigm was previously reported, it is noteworthy that we did not observe a clear effect of task success on implicit adaptation. While the groups in Experiment 1 included more participants (16) than the previous report on effects of target size on implicit adaptation (12), it is possible that our sample did not provide sufficient statistical power to detect an effect of task success. We note that the difference in asymptotic performance between the Hit (mean ± SEM: 9.40° ± 1.14°) and Straddle groups (12.14° ± 1.17°) observed here would correspond to a small-to-medium effect size (Cohen's d = 0.42) – much smaller than the very large effect size ($d = 1.73$) previously reported. Given the complexity of Experiment 1's design, it is not clear whether the effect of task success cues is smaller than that previously observed, or whether the inclusion of monetary reward as a factor throughout the study disrupted the efficacy of the task success cues. To address the lack of a convincing replication of effects of target size on implicit motor adaptation, we simplified our experimental design, employed visual feedback more clearly consistent with task failure, and solely manipulated target size to influence task success in Experiment 2.

Table 1. Details of two-way between subjects ANOVAs conducted for Experiment 1

Factor	F	df_n	df_d	p
Early Learning Rate				
Monetary Cue (Penny [¢]/Dollar [$])	2.44	1	60	0.12
Target Size Condition (Hit/Straddle)	3.06	1	60	0.085
Money x Target Size Interaction	0.36	1	60	0.55
Asymptotic Adaptation				
Monetary Cue (Penny [¢]/Dollar [$])	0.74	1	60	0.39
Target Size Condition (Hit/Straddle)	2.76	1	60	0.10
Money x Target Size Interaction	0.23	1	60	0.63
Change in Asymptote after Monetary Cue Switch				
Monetary Switch (¢ to $/$ to ¢)	2.94	1	60	0.09
Target Size Condition (Hit/Straddle)	1.06	1	60	0.31
Money x Target Size Interaction	0.88	1	60	0.35
Retention				
Monetary Switch History (¢ to $/$ to ¢)	1.04	1	60	0.31
Target Size Condition (Hit/Straddle)	0.71	1	60	0.40
Money x Target Size Interaction	3.85	1	60	0.054

Note. Abbreviations: df, degrees of freedom.

Experiment 2: Does manipulating task outcome via target size alone influence implicit motor learning?

In Experiment 2, we replicated the approach and conditions of Kim and colleagues' (2019) first experiment, including employing the same 3.5° error-clamp size (see *Methods* for additional details). To maximize the likelihood that we would observe an effect, we tested the two most distinct task success conditions: Hit, as described for Experiment 1, and Miss (cursor never touched the target, **Fig. 2A** inset, top). Based on a power analysis of the differences between asymptotic performance in Kim et al.'s Miss and Hit groups, we included 24 participants in each group (total n = 42; see *Methods* for details of the power analysis).

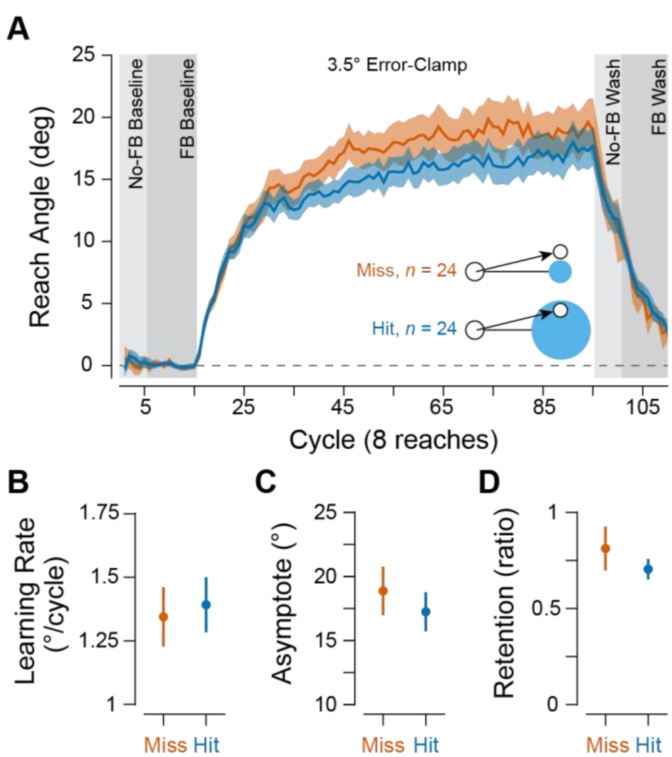

Figure 2. Effects of Target Size-based manipulations on implicit adaptation in Experiment 2. (**A**) Learning curves during Experiment 2. Participants in both the Miss (orange) and Hit (blue) groups exhibited robust changes in hand angle in response to the error-clamp perturbation. (**B**) Early learning rates during Experiment 2. Learning rate was quantified as the mean change in reach angle per cycle across the first 5 cycles of the experiment. (**C**) Asymptotic learning during Experiment

2. Asymptotic learning was quantified as the mean reach angle across the last 10 cycles of the error-clamp block. (**D**) Retention during the no-FB washout block in Experiment 2. Retention was quantified as the ratio of reach angle in the final cycle of the no-FB washout block to the reach angle in the final cycle of the error-clamp block. Data are shown as mean ± standard error of the mean. Abbreviations: FB, feedback.

Both the Hit and Miss groups showed substantial adaptation of reach angles opposite the direction of the error-clamp (**Fig. 2A**). However, we did not observe statistically significant effects of task success on early learning rates (Student's two-sample t-test, $t(46) = -0.30$, $p = 0.77$, **Fig. 2B**) or asymptotic learning ($t(46) = 0.67$, $p = 0.51$, **Fig. 2C**), or retention ($t(46) = 0.85$, $p = 0.40$, **Fig. 2D**). Although the degree of adaptation exhibited by the Hit group (mean ± SEM, 17.24° ± 1.52°) was numerically lower than that of the Miss group (18.88° ± 1.90°), the difference between group mean asymptotes observed here corresponds to a small effect size (*Cohen's d* = 0.08) – smaller than the small-to-medium effect size of Experiment 1 and the very large effect size seen by Kim and colleagues.

The aforementioned analysis used the analysis procedures of Kim and colleagues and could not detect any significant effects of Target Size on adaptation. However, a qualitative trend can be seen where mean adaptation in the Miss group is greater than adaptation in the Hit group for the entire error-clamp block. As an exploratory, post-hoc test, we compared performance averaged over the entire block but still found no statistically significant differences in the degree of adaptation (unpaired t-test, $t(46) = 1.05$, $p = 0.30$). In one final test, we compared performance during the error-clamp cycle exhibiting the greatest differences between the Miss and Hit groups (cycle 45), but still could not detect any significant differences ($t(46) = 1.69$, $p = 0.10$).

Therefore, our data suggest either that manipulating task success via target size does not affect implicit adaptation, or that the magnitude of the effect is much smaller than previously reported. This latter interpretation is consistent with the possibility of a "Decline Effect", wherein an initially reported effect size is larger than those observed later (Protzko and Schooler 2017). However, it is also possible that individual participants' interpretations of what degree of cursor accuracy constitutes "good performance" may affect subjective experiences of task success during the error-clamp manipulations. In this case, differences in participants' experiences of task success between our sample and the sample collected by Kim et al. (2019) may account for differences in our results. To address this, we conducted another experiment that included auditory cues to clarify the task success conditions to participants.

Experiment 3: Does clarifying task success conditions with auditory feedback reveal an effect of task success on implicit adaptation?

To address the possibility that Target Size differences alone failed to affect participants' perceptions of task success during Experiment 2, we provided additional, auditory task success cues in Experiment 3. As in Experiment 2, participants (*n* = 96) either reached to a large target that encompassed the clamped cursor feedback (Hit) or a small target that excluded the clamped cursor feedback (Miss). In addition to these visual task success FB cues, we played auditory FB at the end of the movement.

During the baseline and washout periods, auditory cues were contingent upon hand position at the end of the trial, thereby establishing an association between the auditory FB and participants' perceptions of task success. For participants assigned to "Strict" auditory FB conditions, a pleasant chime sound was played if the hand landed within the radius of the smaller possible target size, regardless of the displayed target size. Otherwise, an unpleasant knocking sound was played. In contrast, participants assigned to the "Lenient" auditory FB conditions heard the pleasant chime sound when the hand landed within the radius of the larger possible target size. At the onset of the

Error-Clamp block, auditory FB became contingent upon the error-clamped cursor FB instead of the hand position such that participants assigned to "Lenient" conditions heard the pleasant chime sound during the 3.5° error-clamp phase whereas participants assigned to the "Strict" conditions heard the unpleasant knocking sound (**Fig. 3A**).

Participants were divided into 4 equally-sized groups according to a 2 x 2 design with 2 levels of auditory cue condition (Strict or Lenient) and 2 levels of task success condition (Hit or Miss, as in Experiment 2). This design allowed us to systematically test whether adding auditory reward and punishment FB to visual indicators of task success would reveal an effect of task performance on implicit adaptation. If auditory FB effectively enhances participants' experiences of task success and task success suppresses implicit adaptation, then participants in the Hit Lenient condition ought to have shown significantly lower levels of asymptotic adaptation relative to participants in the Miss Strict condition.

First, to confirm that participants correctly interpreted the pleasant and unpleasant auditory cues as indicating task success, we examined how participants adjusted their reach angle in response to the auditory FB in the No-FB baseline phase (when they were encouraged to hit the target). During trials with reach endpoints in the range where the tone played varied between groups (*i.e.*, between the small and large target diameters; **Fig. 3A**, left), there was a significant effect of auditory FB condition (two-way between-subjects ANOVA, $F(1,92) = 4.16$, $p = 0.04$, *partial* $\eta^2 = 0.04$) but not target size ($F(1,92) = 0.72$, $p = 0.40$) or the interaction between the two factors ($F(1,92) = 0.02$, $p = 0.88$). A post-hoc t-test confirmed that adjustments in reach angle were greater among participants in the Strict groups (mean ± standard error: 4.82 ± 0.22°) compared to those in the Lenient groups (4.21 ± 0.20; $t(94) = 2.05$, $p = 0.04$, *Cohen's d* = 0.42), indicating that participants the auditory cues were understood by the participants to indicate success or failure.

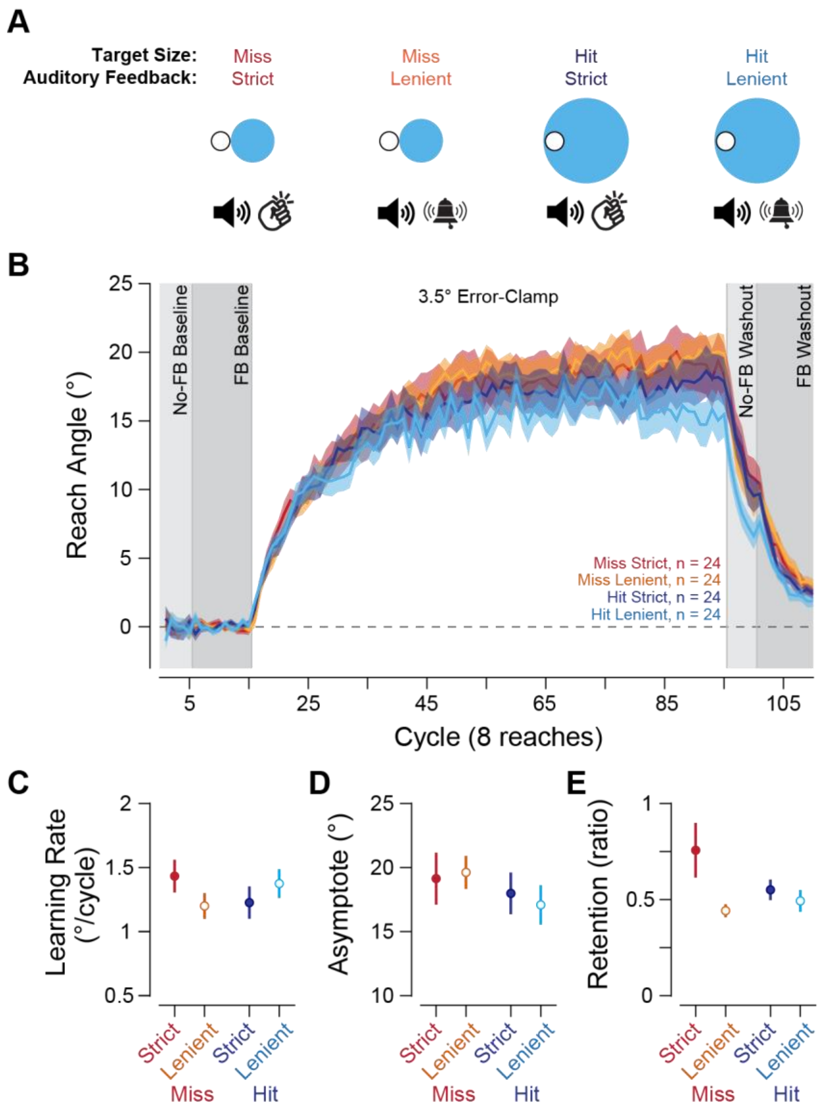

Figure 3. Effects of manipulations of task success using auditory cues in Experiment 3. (**A**) Schematic of visual FB and auditory cues presented to participants during the Error-Clamp block. In Strict conditions (first and third configurations), a knock sound played when the 3.5° error-clamped FB reached the target distance, regardless of target size. In Lenient conditions (second and third configurations), a pleasant dinging sound was played instead. (**B**) Learning curves during Experiment 3. All groups exhibited robust learning in response to the error clamp. (**C**) Early learning rates during Experiment 3. (**D**) Asymptotic learning during Experiment 3. (**E**) Retention ratios during washout of Experiment 3.

Notably, when cursor FB was provided alongside veridical cursor FB in a subsequent baseline phase, auditory FB ceased to influence the magnitude of updates to reach angle within the analyzed window ($F(1,92) = 0.93$, $p = 0.34$), and target size drove differences between groups

($F(1,92) = 7.74$, $p = 0.007$, *partial* $\eta^2 = 0.08$) without an interaction between the factors ($F(1,92) = 0.43$, $p = 0.51$). A post-hoc t-test showed that updates were significantly larger among participants in Miss conditions (small target; mean ± SEM: 3.70 ± 0.12°) than those in Hit conditions (large target; 3.19 ± 0.14°; $t(94) = 2.79$, $p = 0.006$, *Cohen's d* = 0.57). These findings suggest that, when available, visual indicators of task success take precedence in guiding explicit performance over other modalities of performance FB.

During the error-clamp phase, when auditory FB was clamped alongside cursor FB and participants were instructed not to re-aim their movements based on the FB they received, all groups exhibited robust learning to the error clamp (**Fig. 3C**). However, auditory cues, target size, and their interaction had no effect on participants' learning rates (**Fig. 3D**) or asymptotic levels of adaptation (**Fig. 3E;** refer to **Table 2** for details of statistical tests). Thus, even with the addition of auditory cues associated with task performance, task success indicators did not effectively modulate the acquisition of implicit motor adaptation.

Table 2. Details of two-way between subjects ANOVAs conducted for Experiment 3

Factor	F	df_n	df_d	p
Early Learning Rate				
Strict/Lenient Auditory FB	0.13	1	92	0.72
Hit/Miss Target Size Condition	0.02	1	92	0.89
Auditory x Target Size Interaction	2.66	1	92	0.11
Asymptotic Adaptation				
Strict/Lenient Auditory FB	0.02	1	92	0.90
Hit/Miss Target Size Condition	1.27	1	92	0.26
Auditory x Target Size Interaction	0.18	1	92	0.67

Note. Abbreviations: df, degrees of freedom.

During the No-FB washout phase, auditory FB significantly affected retention of implicit adaptation (two-way between subjects ANOVA, $F(1,92) = 5.06$, $p = 0.03$, *partial* $\eta^2 = 0.05$) while target size ($F(1,92) = 0.88$, $p = 0.35$) and the interaction ($F(1,92) = 2.41$, $p = 0.12$) had no effect on retention (**Fig. 3F**). A post-hoc t-test indicated that retention was greater among participants in the Strict condition (mean ± standard error: 0.65 ± 0.08 retention ratio) than participants in the Lenient condition (0.47 ± 0.03 retention ratio; two-sample t-test, $t(94) = 2.23$, $p = 0.03$, *Cohen's d* = 0.46). This suggests that auditory FB may influence the rate of decay of implicit adaptation. However, we note that participants in the Lenient auditory conditions experienced an abrupt shift from hearing the pleasant to the unpleasant tone at the onset of the washout block when auditory feedback was released from the clamp perturbation and became contingent on reach angle. Indeed, many participants in the Lenient group noted the abrupt change and verbally questioned the experimenter about it, but this was not the case for the Strict group. So, it is unclear whether retention of implicit adaptation was suppressed by exposure to the pleasant tone during training, or whether performance in the Lenient conditions was disrupted by an auditory startle response or re-aiming in an attempt to control the auditory FB.

Notwithstanding a potential effect of auditory reward FB on retention of implicit adaptation, the addition of performance-related auditory cues did not substantially affect the rate or degree of implicit adaptation. This is in line with the results of Experiments 1 and 2, providing further evidence that manipulating task success does not affect implicit adaptation, or the effect is quite small. Furthermore, the lack of an effect of auditory cues in Experiment 3 is consistent with the lack of an effect of monetary cues in Experiment 1: there do not appear to be strong effects of appetitive or reward-related cues. In sum, the results of these first three experiments converge to suggest that the effect of task success on implicit motor learning is not mediated by reward, and that the effect observed by manipulating task success via changes in target size is either small or nonexistent. Thus, we sought to assess whether another method for manipulating task success – the so-called "Target Jump" after the fashion of Leow and colleagues (2018) and Tsay and colleagues (2022) – influences implicit adaptation.

Experiment 4: Do task success manipulation using Target Jumps influence implicit motor learning?

In Experiment 4, we aimed to replicate recent work employing a different form of task success manipulation – the Target Jump – that demonstrated an effect on single-trial learning (STL; Tsay et al. 2022). During Target Jump manipulations, the target is displaced partway through the trial so that the cursor feedback lands at an experimenter-specified distance from the center of the target (**Fig. 4A**, top), thereby manipulating task success without manipulating the size of the target. As Target Jumps have been shown to modulate learning in block designs (Leow et al. 2018, 2020), we suspected that replications of an effect of jumping the target may prove more forthcoming.

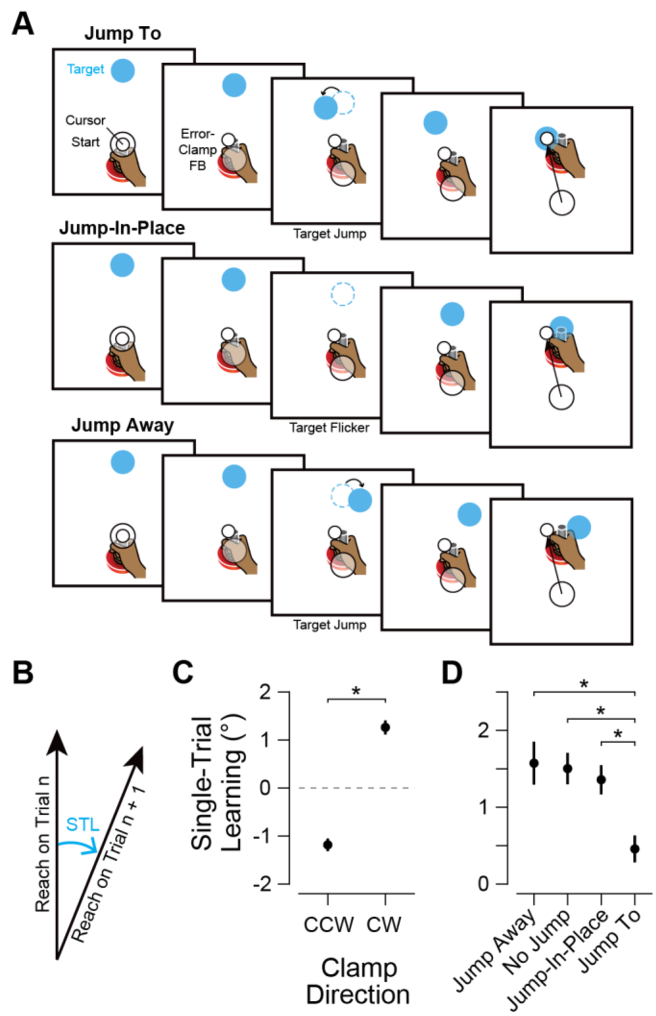

Figure 4. Effects of Target Jump manipulations on single-trial, implicit adaptation. (**A**) Schematic illustrating the different Target Jump perturbations. (**B**) Schematic showing how single-trial learning (STL) was computed for this experiment. (**C**) STL in response to either counterclockwise or clockwise error-clamped FB. Positive STL indicates a counterclockwise change in reach angle, while negative STL indicates a clockwise change. (**D**) STL in response to 4° error-clamped cursor FB paired with the Target Jump manipulations indicated on the x-axis. For this panel, STL has been computed such that positive STL indicates adaptation in the direction opposite the error-clamp (*i.e.*, error-appropriate adaptation), and negative STL indicates adaptation in the same

direction as the error-clamp. * indicates adjusted p-values < 0.05. Abbreviations: FB - feedback, STL - single-trial learning.

Participants (n = 18) were instructed to reach directly for the target that appeared and ignore any deflections in cursor FB or movement of the target, after the fashion of Tsay et al. (2022). After a baseline period with veridical FB, all trials provided 4° error-clamped FB and one of four possible target perturbation events halfway through each reach. The direction of the error-clamped FB (clockwise or counterclockwise) was randomly varied across trials to maintain an average background level of 0° of accumulated adaptation, and adaptation in response to each error/Target Jump combination on trial n was quantified as the difference in reach angles on trials n and $n + 1$ (STL, **Fig. 4B**). "Jump-To" trials, where the target was displaced by 4° such that endpoint cursor FB would fall on the center of the target (**Fig. 4A**, top), were included to assess whether eliminating task error via a Target Jump would affect implicit adaptation. "Jump-Away" trials, where the target was displaced by 4° away from the direction of the error-clamp, were included to assess whether increasing task error via a Target Jump would affect implicit adaptation (**Fig. 4A**, middle). "Jump-In-Place" trials, where the target disappeared for one frame, were included to control for potential attentional effects of the disappearance of the target in Jump-To and Jump-Away trials (**Fig. 4A**, middle), Finally, "No-Jump" trials, where the target was not perturbed during the trial, were included to provide a baseline rate of learning.

Participants showed robust, direction-specific STL in response to error-clamped feedback (one-way within-subjects ANOVA, $F(1,17) = 94.7$, $p = 2.3 \times 10^{-8}$, *partial* $\eta^2 = 0.84$; **Fig. 4C**) that was, as reported by Tsay et al., affected by target manipulations ($F(1.16, 19.8) = 8.80$, $p = 0.006$, *partial* $\eta^2 = 0.23$). In line with the previous report, Jump-To target perturbations significantly suppressed adaptation relative to No Jump (paired t-test, $t(17) = 3.36$, $p_{adj} = 0.02$, *Cohen's d* =

1.43), Jump-Away ($t(17) = 2.89$, $p_{adj} = 0.02$, *Cohen's d* = 1.26), and Jump-In-Place trials ($t(17) = 3.12$, $p_{adj} = 0.02$, *Cohen's d* = 1.28, **Fig. 4D**). Contrary to the report by Tsay et al. (2022), we did not observe a significant effect of Jump-In-Place perturbations on adaptation ($t(17) = 1.96$, $p_{adj} = 0.1$). Given the lack of other significant differences between the conditions, the observation that only Jump-To target perturbations influence STL without attentional effects of Jump-In-Place trials or STL-enhancing effects of Jump-Away perturbations is not clearly consistent with graded effects of task success on implicit adaptation due to attentional distraction induced by the Target Jump.

The robust effects of Target Jumps on implicit adaptation replicated in Experiment 4 stand in stark contrast to the small-to-nonexistent effects of Target Size manipulations reported earlier in this manuscript. Noting that the effects of Target Size appeared larger (albeit still not significant) during Experiment 1, which employed a smaller error-clamp manipulation than Experiments 2-3, we speculated that effects of Target Size may be contingent upon error-clamp size. Such an error size-sensitivity would be consistent with prior work suggesting that the influence of reinforcement decays with the square of the sensory prediction error size (Cashaback et al. 2017). Notably, Target Jump manipulations may enjoy a degree of immunity to changes in error-clamp size as their effects have been observed with perturbations upwards of 30 degrees. Experiment 5 addresses these hypotheses.

Experiment 5. How do Target Size and Target Jump manipulations influence implicit motor learning at various error sizes?

Experiment 5 employed multiple error-clamp sizes, Target Size manipulations (as in Experiments 1-3), and the Target Jump manipulation (as in Experiment 4). This was done in order to comprehensively assay the effect of each manipulation at various error sizes, as other results have suggested that the effect of reinforcement plays a greater role at small error sizes (Cashaback et al. 2017). Participants (n = 42) were instructed to move straight toward the target that appeared on the screen, regardless of cursor FB, which would be clamped away from the center of the target by an angular error that randomly varied on each trial between 1.75° and 10.5°, at increments of 1.75°. Additionally, on a given trial, the target would be a) small enough that even the 1.75° clamp would miss the target (Miss; **Fig. 2A** inset top), b) large enough that even the 10.5° clamp would be entirely within the target (Hit; **Fig. 1C bottom**), or c) the target, at the same size as the Miss target, would jump to meet the cursor FB, eliminating task error (Jump-To; **Fig. 4A top)**. Clamp direction (clockwise or counterclockwise) varied across trials with zero-mean, allowing us to measure single-trial learning (STL) as the change in hand angle on trial t+1 in response to the error observed on trial t.

Participants exhibited robust STL which tracked the error magnitude and direction (stats, **Fig. 5A**). A two-way repeated-measures ANOVA highlighted a statistically significant effect of error-clamp magnitude (F(3.66, 150.05) = 62.14, p = 2.24 x 10^{-29}, η_G^2 = 0.20) and task success condition (F(1.61, 65.99) = 17.96, p = 3.38 x 10^{-6}, η_G^2 = 0.08), but no interaction (F(10, 410) = 0.97, p = 0.47). STL was significantly suppressed relative to the Miss condition by both Hit (t(41) = 4.04, p_{adj} = 9.54 x 10^{-4}, *Cohen's d* = 0.50) and Jump-To FB (t(41) = 5.36, p_{adj} = 2.48 x 10^{-5}, *Cohen's d* = 0.91), although STL was suppressed more by Jump-To FB than Hit FB (t(41) = 2.79, p_{adj} = 0.02, *Cohen's d* = 0.49; **Fig. 5B**).

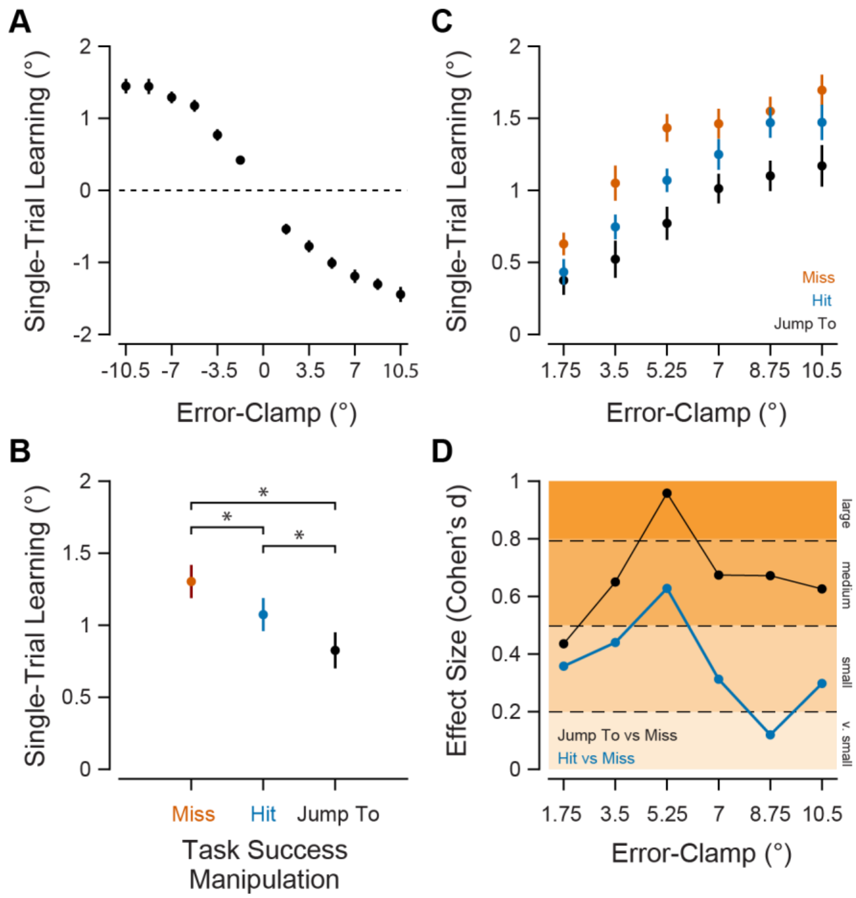

Figure 5. Effects of Target Size, Target Jump, and error-clamp size manipulations on single-trial, implicit adaptation. (**A**) STL in response to either counterclockwise or clockwise error-clamped FB, collapsed across task success conditions. Positive STL indicates a counterclockwise change in reach angle, while negative STL indicates a clockwise change. (**B**) STL collapsed across error-clamp magnitude/direction but separated by task success condition. Positive STL indicates a change in reach angle opposite the direction of the observed error-clamp. Boxplot center: median, box edges: 1st and 3rd quartiles, notch: 95% confidence interval of the median, whiskers: most extreme values not considered outliers. (**C**) STL in response to error-clamped FB collapsed across direction but separated by error-clamp magnitude and task success condition. (**D**) Effect size measures (*Cohen's d*) of the differences between the Miss condition and the Jump To (black) or the Hit (blue) conditions as a function of the magnitude of the error-clamp. Orange shading and labels on the right hand side of the panel indicate descriptions of effect sizes according to Cohen's (1988) thresholds guidelines. * indicates adjusted p-values < 0.05. Abbreviations: STL - single-trial learning.

Subsequent pre-planned post-hoc pairwise comparisons provided further evidence that the Jump-To manipulation generally suppressed STL more than the Hit manipulation. While participants exhibited significantly less STL on Jump-To trials than Miss trials for all error-clamp magnitudes greater than 1.75°, participants only exhibited less STL on Hit trials relative to Miss trials at 3.5° and 5.25° error-clamps (**Fig. 5C**, see **Table 3** for statistical details). In addition, STL was significantly lower in the Jump-To than the Hit condition at 5.25° and 8.75° error-clamps (**Fig. 5C**, **Table 3**). Moreover, differences in STL between Miss and Jump-To conditions exhibited larger effect sizes than differences between Miss and Hit conditions at all error-clamp magnitudes greater than 1.75° (**Fig. 5D**, **Table 3**).

Taken together, the results of Experiment 5 illustrate that the Jump-To manipulation generally elicits a larger and more reliable suppression of STL than the Hit manipulation for nearly all error sizes. However, the data do not provide clear support for the claim that the effect of the Hit manipulation becomes weaker as the magnitude of the error-clamp increases. Overall, there is a slight reduction of Hit effect size with increases in error-clamp magnitude, but the jump in effect size at 5.25° degrees disrupts this trend (**Fig. 5D**). We note that there were no extreme outliers (STL beyond 3 standard deviations from the mean) in the Miss or Hit conditions driving this change in effect size.

Table 3. Details of pre-planned post-hoc pairwise comparisons conducted for Experiment 5 (comparisons in Fig. 5C)

Task Success x Reward A	Task Success x Reward B	t	p	p_{adj}	Signif.	Cohen's d
Miss x 1.75°	Hit x 1.75°	1.62	0.11	0.13		0.36
Miss x 3.5°	Hit x 3.5°	2.39	1.2×10^{-4}	0.04	*	0.44
Miss x 5.25°	Hit x 5.25°	3.49	0.001	0.003	*	0.63
Miss x 7°	Hit x 7°	1.80	0.08	0.12		0.31
Miss x 8.75°	Hit x 8.75°	0.74	0.5	0.49		0.12
Miss x 10.5°	Hit x 10.5°	1.84	0.07	0.12		0.30
Miss x 1.75°	Jump To x 1.75°	1.72	0.09	0.13		0.43
Miss x 3.5°	Jump To x 3.5°	3.12	0.003	0.008	*	0.65
Miss x 5.25°	Jump To x 5.25°	5.49	2.3×10^{-6}	3.7×10^{-5}	*	0.96
Miss x 7°	Jump To x 7°	4.07	2.1×10^{-4}	0.001	*	0.67
Miss x 8.75°	Jump To x 8.75°	3.57	9.1×10^{-4}	0.003	*	0.67
Miss x 10.5°	Jump To x 10.5°	3.93	3.2×10^{-4}	0.001	*	0.63
Hit x 1.75°	Jump To x 1.75°	0.50	0.62	0.62		0.09
Hit x 3.5°	Jump To x 3.5°	1.38	0.17	0.19	*	0.32
Hit x 5.25°	Jump To x 5.25°	2.30	0.03	0.046	*	0.46
Hit x 7°	Jump To x 7°	1.66	0.1	0.13		0.35
Hit x 8.75°	Jump To x 8.75°	3.11	0.003	0.008	*	0.54
Hit x 10.5°	Jump To x 10.5°	1.67	0.1	0.12		0.35

Note. All comparisons' degrees of freedom are equal to 41. Familywise error rates were maintained by adjusting p-values according to the false discovery rate method, accounting for the comparisons made in **Fig. 5B-C**. Comparisons reaching statistical significance ($p_{adj} < 0.05$) are flagged with a ***.**

DISCUSSION

On the whole, our findings add to a body of work suggesting that task success modulates implicit adaptation, but they do not support the idea that implicit adaptation is sensitive to reward. The results of our initial experiments suggest that implicit motor adaptation is not modulated by auditory or monetary reward cues (**Figs. 1, 3**), and the studies throughout this manuscript illustrate that implicit motor adaptation is only weakly modulated when the cursor lands inside the target but not at its center (**Figs. 1-3**, **5**). Furthermore, our data suggest that Target Jumps are the most reliable approach for suppressing implicit adaptation via task success manipulations (**Figs. 4-5**).

Implicit adaptation is not influenced by reward expectation

Implicit motor adaptation did not exhibit clear sensitivity to either monetary (**Fig. 1**) or auditory reward expectation (**Fig. 3**). Although we observed a significant effect of auditory cue on retention ratios during Experiment 3, we believe that this effect arose from re-aiming or error-based learning rather than the implicit system. During the washout phase without visual FB, auditory FB was once again contingent upon reach angle. As a result of residual adaptation from the error-clamp block, participants in the Strict group were likely to miss the target during the initial washout block and thus unlikely to experience a change in auditory FB. On the other hand, the auditory FB contingency transition was obvious for the Lenient group, which heard pleasant chimes throughout the error-clamp block but began hearing unpleasant knocks in the washout because their reaches had adapted away from the target location. Because a sudden change in auditory FB can drive changes in action selection (Nikooyan and Ahmed 2015), the retention measurement for the Lenient group may have been contaminated by explicit learning, rather than purely reflecting the rate of decay of implicit adaptation. Given the lack of other statistically significant effects on uncontaminated parameters in this experiment, we conclude that auditory cues are not likely to modulate implicit adaptation.

Together, Experiments 1 and 3 suggest that the implicit adaptation system does not process reward value. Notably, these particular experiments used block designs and exhibited null effects of both reward value and Target Size, while Experiment 5 leveraged a single-trial learning design and revealed significant effects of Target Size. One may wonder, then, how conclusively Experiments 1 and 3 rule out effects of reward on implicit adaptation, and whether we might detect effects of reward in single-trial experiments. However, we note that the effect of Target Size in Experiment 5 ranged from small to very small for most error magnitudes tested (**Fig. 5D**). This suggests that, if any effect of reward on implicit adaptation is detectable in the context of a single-trial learning paradigm, it would be a small effect without much practical significance. By extension, we propose that most of the effects of reward on motor learning act through explicit components of motor control, such as action selection (Chen et al. 2018; Izawa and Shadmehr 2011; Nikooyan and Ahmed 2015; Taylor and Ivry 2012).

Target jumps exert more reliable effects on implicit adaptation than target size manipulations

The block designs of Experiments 1-3 provided very little evidence for task success effects using Target Size manipulations. In fact, Experiments 2 and 3 notably failed to produce any effect of hitting the target, while Experiment 1 elicited only a trend towards an effect. This stands in stark contrast with the large effects reported by Kim and colleagues (2019). Upon noting that Experiment 1 employed a smaller error-clamp size than Experiments 2 and 3 but exhibited something closer to a statistically significant effect of Target Size, we investigated whether Target Size manipulations elicited effects only at smaller sensory-prediction error magnitudes. Somewhat supporting this hypothesis, Experiment 5 uncovered statistically significant effects of the Target Size manipulation only at 3.5° and 5.25°, and numerical effects of Target Size for error-clamps less than 7°. Target Jump manipulations, on the other hand, elicited far stronger evidence for an effect of task success on implicit motor adaptation (**Fig. 4 & 5**), and this result was robust across all tested error-clamp magnitudes greater than 1.75° (**Fig. 5**).

While it is clear that Target Jump manipulations more reliably produce a task success effect than Target Size manipulations, the question remains as to why. It may be that the Target Size and Target Jump manipulations lie along a spectrum of task success manipulations, and that Target Size more weakly modulates adaptation because the cursor does not lie as close to the center of the target and cannot be interpreted as wholly successful. In line with this possibility, a change in target position during a Target Jump may 1) change the participant's experience of "task error" to modulate adaptation in a graded fashion and 2) draw attentional resources and detracts from implicit adaptation processes (Tsay et al. 2022). Although our data do not fully support this explanation, they also do not clearly refute it. We did not observe an increase in the amount of adaptation observed during Jump-Away trials, suggesting that increases in task error measured as the distance between the cursor and the center of the target do not exert a graded effect on adaptation. Furthermore, we did not observe a detrimental effect of briefly removing the target (Jump-In-Place, **Fig. 4**) that would allow us to infer that enhanced adaptation was masked by jump-related-distraction in the Jump-Away condition. However, considering that the amount of single-trial implicit adaptation observed saturated around error-clamp magnitudes of 5.25° in the Miss condition (**Fig. 5**), it is possible that we failed to observe an enhancement of adaptation in the Jump-Away condition with the 4° error-clamp used in Experiment 4 due to a ceiling effect. Thus, while our data are not wholly consistent with the idea that there is a continuous task error variable that modulates implicit adaptation in a graded fashion, it seems plausible that the Target Jump manipulation may be read as greater task success and thereby have a greater impact on implicit adaptation than Target Size manipulations.

Mechanisms underlying effects of task success on implicit adaptation

Our experiments showed that implicit adaptation is not likely to be influenced by rewards such as money or auditory performance cues, while we report effects of task success, indicating that hitting the target can attenuate adaptation. These results raise the question: Why do task success cues but not rewards affect implicit adaptation? We suggest that sensory prediction errors and task errors are feedback signals inherent to motor tasks – detecting and processing these signals are essential components of assessing motor plan execution. Rewards and other performance cues, on the other hand, are often dictated by variable, context-dependent contingencies (*e.g.*, a basketball free-throw during practice will not be met with as much fanfare as a free-throw that wins a game) and are not intrinsically related to the performed movement. As such, implicit adaptation may be sensitive only to feedback that is most directly pertinent to the internal model, namely sensory-prediction error and visually-indicated task success, as opposed to reward. While other sensorimotor learning processes have been shown to be sensitive to rewards (Codol et al. 2023), we suggest that the implicit adaptation process studied here is relatively immune to reward effects.

Considering that visuomotor reach adaptation is a cerebellar-dependent task (Butcher et al. 2017; Morehead et al. 2017) and that recent work has highlighted that the cerebellum processes reward (Heffley and Hull 2019; Kostadinov et al. 2019; Larry et al. 2019; Wagner et al. 2017), this finding may seem surprising. However, the cerebellum is composed of many parallel modules and microcircuits that are involved in different tasks (Apps and Garwicz 2005; Apps and Hawkes 2009), and reward signals have not been observed in all microzones. Thus, it is possible that reward-based learning and sensory-prediction error-based learning proceed in largely parallel cerebellar circuits. By extension, the specific cerebellar microzones involved in implicit reach adaptation may be insensitive to reward, despite the fact that reward may play a role in tasks dependent on other cerebellar circuits and the popular presupposition of a single cerebellar computation (Diedrichsen et al. 2019; Kostadinov and Häusser 2022). Indeed, the idea that cerebellar circuits for implicit motor learning and reward processing are divided is supported by observations that patients with cerebellar degeneration can engage in many aspects of typical reward-driven reinforcement learning despite showing substantial deficits in adaptation (Morehead et al. 2017; Nicholas et al. 2022; Therrien et al. 2016). Such a division of reward-based and sensory prediction error-based learning would be consistent with classical observations of differences between sensory-prediction error-based supervised motor learning and reinforcement learning (for review see Gershman and Uchida 2019; Raymond and Medina 2018).

While this is an important clarification, as previous work has emphasized a role for reward in mediating the effects of task success (Kim et al. 2019), the mechanism by which task success influences adaptation has yet to be specified. It seems unlikely that task success acts as a teaching signal that drives learning independently (Kim et al. 2019; Morehead and de Xivry 2021), because implicit adaptation only occurs in the presence of sensory prediction errors and does not proceed on task error alone (Tsay et al. 2022). Future work will be necessary to solidly identify the process-level mechanisms by which task success influences implicit adaptation.

Summary

In the present article, we attempted to replicate previous findings that hitting a target attenuates implicit motor learning and probe various theoretical explanations for this effect. The results of the five experiments presented above suggest that implicit motor adaptation is at most weakly modulated by task success as defined by the cursor hitting the target, and this effect is not driven by monetary or auditory rewards. The attenuation of learning driven by shifting the target to be concentric with the final cursor location vastly exceeded the attenuation due to hitting a larger target that remained stationary, indicating that perhaps these two different manipulations influence motor learning in different manners. These results highlight that hitting the center of the target reliably influences implicit motor adaptation, but that rewards and more abstract signals of task success may not have practically significant effects on implicit learning.

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Table 1. Details of two-way between subjects ANOVAs conducted for Experiment 1

Factor	F	df_n	df_d	p
Early Learning Rate				
Monetary Cue (Penny [¢]/Dollar [$])	2.44	1	60	0.12
Target Size Condition (Hit/Straddle)	3.06	1	60	0.085
Money x Target Size Interaction	0.36	1	60	0.55
Asymptotic Adaptation				
Monetary Cue (Penny [¢]/Dollar [$])	0.74	1	60	0.39
Target Size Condition (Hit/Straddle)	2.76	1	60	0.10
Money x Target Size Interaction	0.23	1	60	0.63
Change in Asymptote after Monetary Cue Switch				
Monetary Switch (¢ to $/$ to ¢)	2.94	1	60	0.09
Target Size Condition (Hit/Straddle)	1.06	1	60	0.31
Money x Target Size Interaction	0.88	1	60	0.35
Retention				
Monetary Switch History (¢ to $/$ to ¢)	1.04	1	60	0.31
Target Size Condition (Hit/Straddle)	0.71	1	60	0.40
Money x Target Size Interaction	3.85	1	60	0.054

Note. Abbreviations: df, degrees of freedom.

Table 2. Details of two-way between subjects ANOVAs conducted for Experiment 3

Factor	F	df_n	df_d	p
Early Learning Rate				
Strict/Lenient Auditory FB	0.13	1	92	0.72
Hit/Miss Target Size Condition	0.02	1	92	0.89
Auditory x Target Size Interaction	2.66	1	92	0.11
Asymptotic Adaptation				
Strict/Lenient Auditory FB	0.02	1	92	0.90
Hit/Miss Target Size Condition	1.27	1	92	0.26
Auditory x Target Size Interaction	0.18	1	92	0.67

Note. Abbreviations: df, degrees of freedom.

Table 3. Details of pre-planned post-hoc pairwise comparisons conducted for Experiment 5 (comparisons in Fig. 5C)

Task Success x Reward A	Task Success x Reward B	t	p	p_{adj}	Signif.	Cohen's d
Miss x 1.75°	Hit x 1.75°	1.62	0.11	0.13		0.36
Miss x 3.5°	Hit x 3.5°	2.39	1.2×10^{-4}	0.04	*	0.44
Miss x 5.25°	Hit x 5.25°	3.49	0.001	0.003	*	0.63
Miss x 7°	Hit x 7°	1.80	0.08	0.12		0.31
Miss x 8.75°	Hit x 8.75°	0.74	0.5	0.49		0.12
Miss x 10.5°	Hit x 10.5°	1.84	0.07	0.12		0.30
Miss x 1.75°	Jump To x 1.75°	1.72	0.09	0.13		0.43
Miss x 3.5°	Jump To x 3.5°	3.12	0.003	0.008	*	0.65
Miss x 5.25°	Jump To x 5.25°	5.49	2.3×10^{-6}	3.7×10^{-5}	*	0.96
Miss x 7°	Jump To x 7°	4.07	2.1×10^{-4}	0.001	*	0.67
Miss x 8.75°	Jump To x 8.75°	3.57	9.1×10^{-4}	0.003	*	0.67
Miss x 10.5°	Jump To x 10.5°	3.93	3.2×10^{-4}	0.001	*	0.63
Hit x 1.75°	Jump To x 1.75°	0.50	0.62	0.62		0.09
Hit x 3.5°	Jump To x 3.5°	1.38	0.17	0.19	*	0.32
Hit x 5.25°	Jump To x 5.25°	2.30	0.03	0.046	*	0.46
Hit x 7°	Jump To x 7°	1.66	0.1	0.13		0.35
Hit x 8.75°	Jump To x 8.75°	3.11	0.003	0.008	*	0.54
Hit x 10.5°	Jump To x 10.5°	1.67	0.1	0.12		0.35

Note. All comparisons' degrees of freedom are equal to 41. Familywise error rates were maintained by adjusting p-values according to the false discovery rate method, accounting for the comparisons made in **Fig. 5B-C**. Comparisons reaching statistical significance ($p_{adj} < 0.05$) are flagged with a ***.**

883

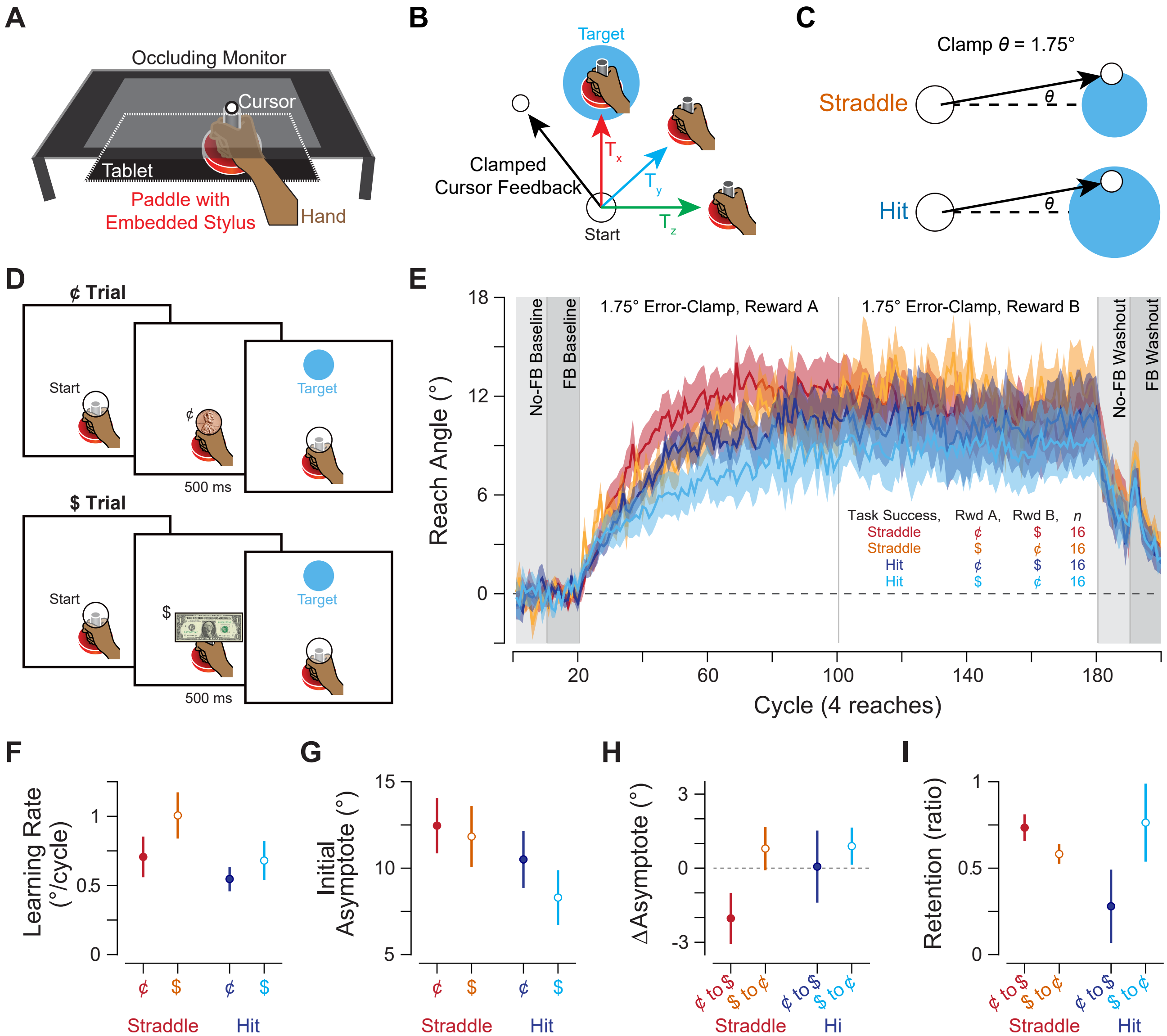

Figure 1. Effects of monetary cues and task success FB on implicit adaptation. (**A**) Experimental apparatus. Participants held a stylus and made reaching movements atop a digitizing tablet. Vision of the arm was occluded by a computer monitor that also displayed task FB. (**B**) Error-clamped cursor FB. During an error-clamp task, the cursor (white) travels along a predetermined trajectory (Clamped Cursor Feedback) relative to the target (blue) regardless of the reach trajectory (T_x, T_y, and T_z). (**C**) Error-clamped visual FB displayed to participants in the Straddle (orange, top) and Hit (blue, bottom) groups. (**D**) Monetary cues were displayed at trial onset. Either a penny (top) or dollar (bottom) was displayed while participants held their hand in the start location before target illumination. (**E**) Learning curves during Experiment 1. Inset table describes which monetary rewards were offered for each block of adaptation. (**F**) Learning rates during the first 5 training blocks of Experiment 1. (**G**) Asymptotic learning at the end of the Reward A training phase in Experiment 1. (**H**) Change in asymptote between the Reward A and B phases in Experiment 1. (**I**) Retention ratios in Experiment 1, with retention ratio defined as the proportion of the adaptation memory observed in the last cycle of no-FB washout relative to the last cycle of training.

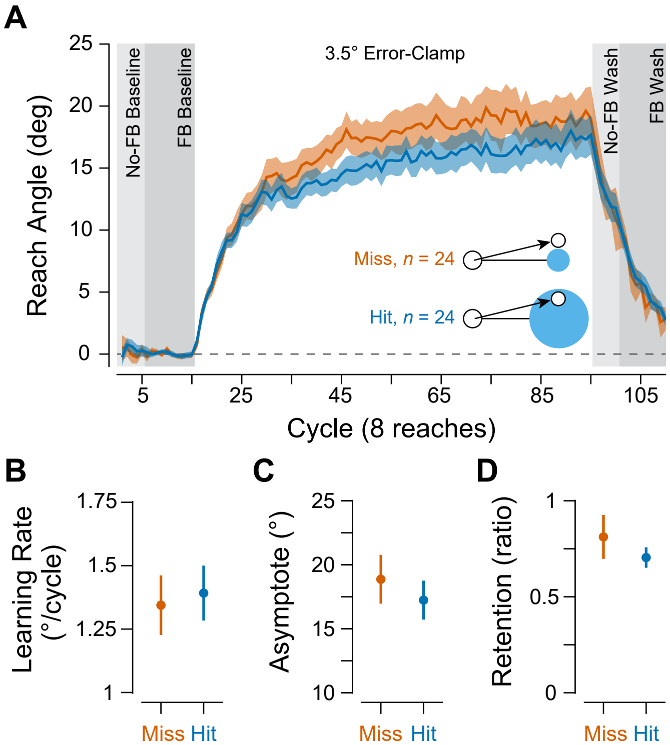

Figure 2. Effects of Target Size-based manipulations on implicit adaptation in Experiment 2. (**A**) Learning curves during Experiment 2. Participants in both the Miss (orange) and Hit (blue) groups exhibited robust changes in hand angle in response to the error-clamp perturbation. (**B**) Early learning rates during Experiment 2. Learning rate was quantified as the mean change in reach angle per cycle across the first 5 cycles of the experiment. (**C**) Asymptotic learning during Experiment 2. Asymptotic learning was quantified as the mean reach angle across the last 10 cycles of the error-clamp block. (**D**) Retention during the no-FB washout block in Experiment 2. Retention was quantified as the ratio of reach angle in the final cycle of the no-FB washout block to the reach angle in the final cycle of the error-clamp block. Data are shown as mean ± standard error of the mean. Abbreviations: FB, feedback.

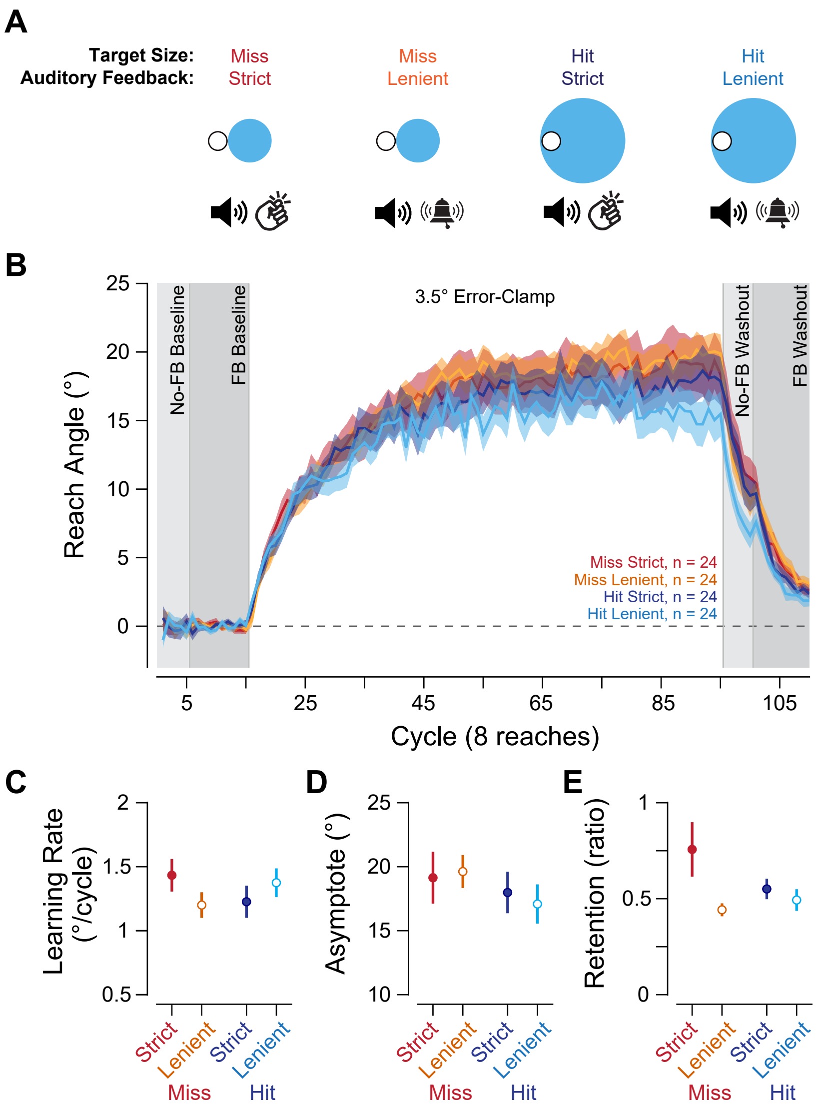

Figure 3. Effects of manipulations of task success using auditory cues in Experiment 3. (**A**) Schematic of visual FB and auditory cues presented to participants during the Error-Clamp block. In Strict conditions (first and third configurations), a knock sound played when the 3.5° error-clamped FB reached the target distance, regardless of target size. In Lenient conditions (second and third configurations), a pleasant dinging sound was played instead. (**B**) Learning curves during Experiment 3. All groups exhibited robust learning in response to the error clamp. (**C**) Early learning rates during Experiment 3. (**D**) Asymptotic learning during Experiment 3. (**E**) Retention ratios during washout of Experiment 3.

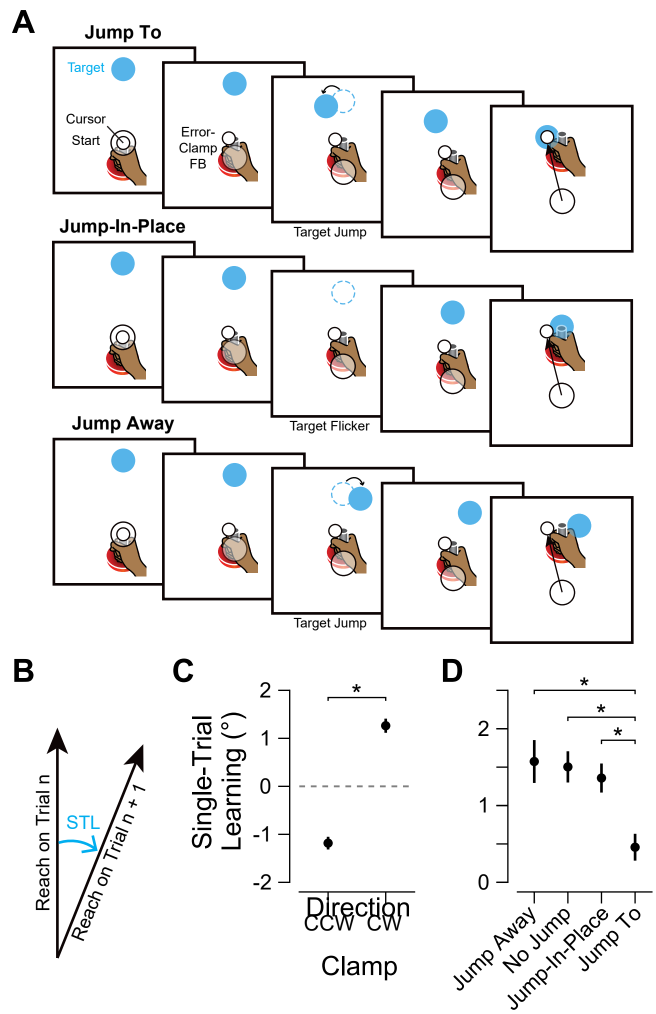

Figure 4. Effects of Target Jump manipulations on single-trial, implicit adaptation. (**A**) Schematic illustrating the different Target Jump perturbations. (**B**) Schematic showing how single-trial learning (STL) was computed for this experiment. (**C**) STL in response to either counterclockwise or clockwise error-clamped FB. Positive STL indicates a counterclockwise change in reach angle, while negative STL indicates a clockwise change. (**D**) STL in response to 4° error-clamped cursor FB paired with the Target Jump manipulations indicated on the x-axis. For this panel, STL has been computed such that positive STL indicates adaptation in the direction opposite the error-clamp (*i.e.*, error-appropriate adaptation), and negative STL indicates adaptation in the same direction as the error-clamp. * indicates adjusted p-values < 0.05. Abbreviations: FB - feedback, STL - single-trial learning.

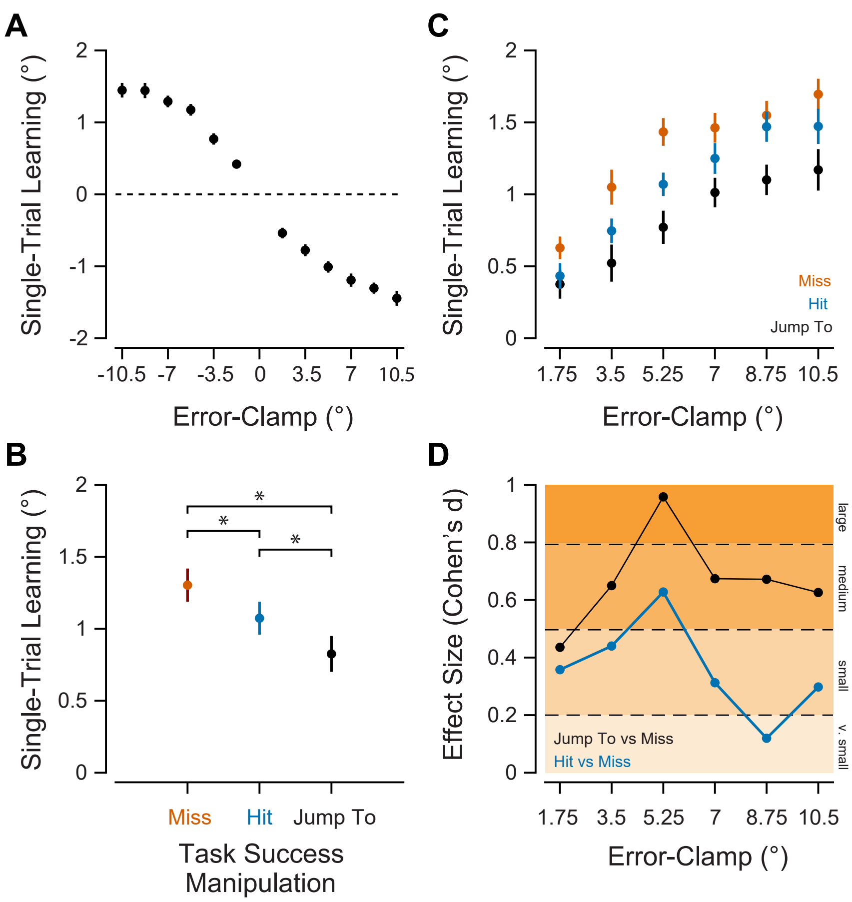

Figure 5. Effects of Target Size, Target Jump, and error-clamp size manipulations on single-trial, implicit adaptation. (**A**) STL in response to either counterclockwise or clockwise error-clamped FB, collapsed across task success conditions. Positive STL indicates a counterclockwise change in reach angle, while negative STL indicates a clockwise change. (**B**) STL collapsed across error-clamp magnitude/direction but separated by task success condition. Positive STL indicates a change in reach angle opposite the direction of the observed error-clamp. Boxplot center: median, box edges: 1st and 3rd quartiles, notch: 95% confidence interval of the median, whiskers: most extreme values not considered outliers. (**C**) STL in response to error-clamped FB collapsed across direction but separated by error-clamp magnitude and task success condition. (**D**) Effect size measures (Cohen's d) of the differences between the Miss condition and the Jump To (black) or the Hit (blue) conditions as a function of the magnitude of the error-clamp. Orange shading and labels on the right hand side of the panel indicate descriptions of effect sizes according to Cohen's (1988) thresholds guidelines. * indicates adjusted p-values < 0.05. Abbreviations: STL - single-trial learning.