Effect of Task Error on Implicit Motor Adaptation

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Abstract

Motor adaptation is essential for maintaining coordination in daily activities. Implicit motor adaptation, operating unconsciously, is primarily considered to be driven by sensory prediction errors. This study aims to investigate how another error signal, task error, affects implicit adaptation across varying perturbation sizes using a visuomotor reaching paradigm. Employing a Single Trial Learning (STL) approach, we compare initial adaptation responses to different target types: a small dot target reinforcing strict spatial accuracy, and a large arc target permitting greater movement endpoint variability. By manipulating target size, we systematically alter task error presence or absence, isolating its influence on implicit motor adaptation, while holding sensory prediction error constant. These findings will advance our understanding of task error and sensory prediction error interactions in the early stages of implicit motor learning. Ultimately, this work aims to refine current motor learning models and inform targeted error type utilization in rehabilitation and training strategies.

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Introduction

Motor adaptation is the process of fine-tuning and adapting movements in response to changing environments and task demands. As such, it is crucial for maintaining coordination and precision in a variety of everyday activities. The way we hold a slippery glass, adapt our stride when walking on uneven ground, or recalibrating movements when using unfamiliar tools all rely on our brain's ability to learn and adapt. These adjustments involve both explicit strategies, such as consciously modifying movements, and implicit contributions, which occur automatically and without deliberate effort. Implicit motor adaptation, in particular, enables seamless corrections in the background, allowing us to adjust grip strength or navigate novel tools without conscious awareness. This form of learning has been proposed to be largely driven by *sensory prediction errors*, discrepancies between expected and actual sensory feedback – which help update our motor system to better match real-world conditions (Mazzoni & Krakauer, 2006; Krakauer et al., 2019; Morehead & Orban, 2021). Without such adaptation, everyday actions would become increasingly difficult as individuals encounter new or dynamic environments.

Visuomotor adaptation paradigms offer a well-controlled method for studying motor adaptation in the laboratory. In these paradigms, participants reach towards targets while receiving altered visual feedback of their unseen reaching hand. This manipulation is typically achieved by displaying a cursor that deviates from the actual hand trajectory, as shown in Fig. 1. A common visuomotor rotation involves shifting the visual representation of the participant's hand by a fixed angle, such as 30° or 45°, relative to the actual trajectory (Mazzoni & Krakauer, 2006; Krakauer et al., 2019; Shadmehr et al., 2010). In response to this perturbation, participants gradually and unconsciously adjust their hand movements in the opposite direction to realign the cursor with the target (Mazzoni & Krakauer, 2006; Krakauer et al., 2019; Shadmehr et al., 2010). Adaptation generally follows an exponential curve, with participants requiring approximately 20 trials to fully compensate for the visual distortion (Krakauer et al., 2000). When the perturbation is removed, participants continue to reach in the adapted direction, producing *reach aftereffects* that reflect adjustments to the internal motor representation (Krakauer et al., 2000; Taylor et al., 2014). These aftereffects persist even when participants are aware of the manipulation, highlighting the contribution of implicit learning mechanisms that operate independently of explicit strategies (Gastrock et al., 2020; Modchalingam et al., 2023; Shadmehr et al., 2010). Explicit strategies are predominantly utilized for larger perturbations, such as rotations of 45° or more, which are more noticeable and easier to consciously correct (Modchalingam et al., 2019; Taylor et al., 2014). However, implicit contributions are consistently observed across a range of perturbation magnitudes, with reach aftereffects typically stabilizing at approximately 15° for rotations of 30° or greater, and up to 90° (Bond & Taylor, 2015; Mazzoni & Krakauer, 2006; Krakauer, 2009; Leow et al., 2017).

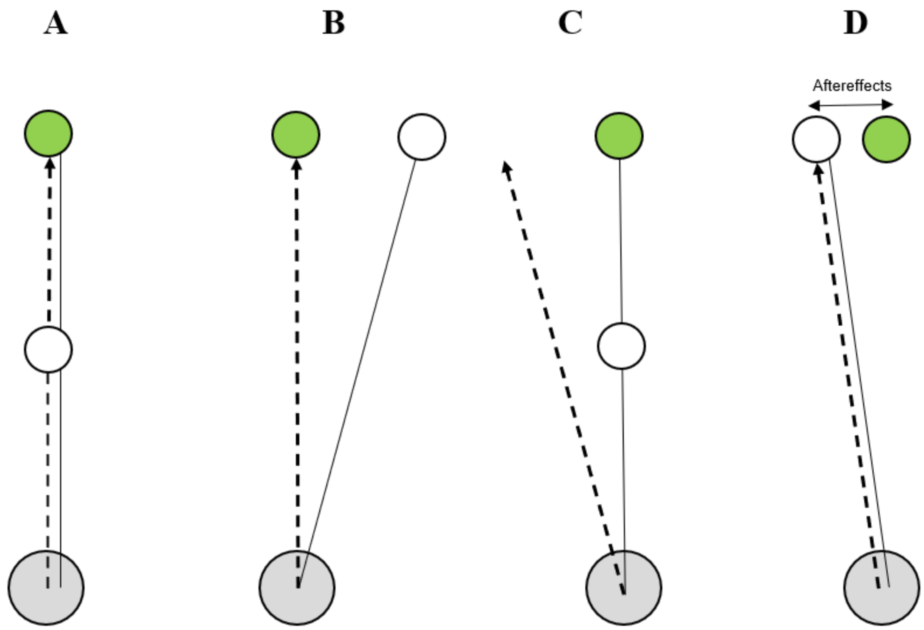

Fig. 1. Example of cursor (white circle) movements to a target (green circle) during a visuomotor adaptation task. (A) During baseline trials with veridical feedback, the cursor (solid line) accurately reflects the hand's movement direction (dashed line). (B) During adaptation, a 30° clockwise rotation is applied to the cursor's movement direction relative to the home position (grey circle), creating a mismatch between the actual hand movement (dashed line) and the visual feedback (solid line). (C) With repeated exposure, participants adapt by adjusting their hand movements counterclockwise to direct the rotated cursor toward the target (green circle). (D) When veridical feedback is reintroduced, participants continue reaching in the adapted direction, resulting in a leftward cursor deviation—an aftereffect that reflects implicit motor adaptation. The grey circle represents the home position from which movement is initiated, the green circle represents the target, and the white circle represents the cursor after each hand movement.

The time course by which these implicit measures develop across different rotation magnitudes remains unclear. This uncertainty stems from the fact that reach aftereffects are typically measured only after extensive training (Taylor et al., 2014; Neville & Cressman, 2018), once adaptation is well underway or nearing completion. As a result, implicit motor learning has traditionally been viewed as a slow process that develops gradually over time (Bond & Taylor, 2015; Mazzoni & Krakauer, 2006; McDougle et al., 2015; Van Es & Knapen, 2019). In this framework, the large initial changes in reach direction observed early in adaptation are typically attributed to explicit strategy use, while the subsequent gradual reduction and stabilization of errors are thought to reflect the slower accumulation of implicit adjustments (Benson et al., 2011; Mazzoni & Krakauer, 2006; McDougle et al., 2015; Van Es & Knapen, 2019).

However, findings from our lab have challenged the view of implicit learning as a slow process. For instance, we have shown that substantial reach aftereffects can emerge after only 6 trials of training with a 30° rotated cursor (Ruttle et al., 2018). In a follow-up study, we measured aftereffects following each individual training trial and found that they emerged and reached near-saturation as early as the third trial (Ruttle et al., 2021). Another study from our lab observed a similarly rapid saturation of aftereffects, after approximately 20 trials, when measured after each individual training trial across various visual feedback conditions (D'Amario et al., 2024). More recently, D'Amario et al. (2024) observed a similarly rapid time course: reach aftereffects plateaued after approximately 20 trials, regardless of the visual feedback condition. In one condition, separate groups were trained with cursor rotations of 15°, 30°, 45°, or 60°, and initial aftereffects consistently appeared at rates of 2° to 4° following just a single trial. These results suggest that implicit learning can occur far more rapidly than previously assumed.

Beyond aftereffect measures, other approaches such as error-clamp paradigms have been used to directly probe implicit learning during visuomotor adaptation. In these paradigms, participants reach toward a target while receiving cursor feedback that moves along a fixed path relative to the target, independent of their actual hand movement. Even when explicitly informed that the cursor is not under their control, participants systematically adjust their unseen hand movements away from the direction of the clamped feedback (Al-Fawakhiri et al., 2023; Kim et al., 2018; Morehead et al., 2017; Zhang et al., 2024). These adjustments reveal an automatic response to sensory prediction errors—discrepancies between expected and actual sensory outcomes—despite the absence of task-related success or error. Such findings provide strong evidence that implicit motor adaptation is primarily driven by sensory prediction error rather than task error (Al-Fawakhiri et al., 2023; Kim et al., 2018; Morehead et al., 2017; Zhang et al., 2024).

While implicit motor learning is primarily driven by sensory prediction error—the discrepancy between expected and actual sensory feedback (Morehead & Orban, 2021; Shadmehr et al., 2010; Tsay et al., 2022)—recent research suggests that task error may also influence implicit adaptation under certain conditions (Galea et al., 2015; Kim et al., 2018; Kim et al., 2019; Leow et al., 2018). Task error, defined as the difference between the intended movement goal and the actual outcome, has traditionally been associated with explicit strategies that involve conscious correction. However, several studies have demonstrated that task error can modulate implicit learning, particularly when experimental manipulations emphasize success or failure (Galea et al., 2015; Kim et al., 2018; Kim et al., 2019).

To isolate the contribution of task error, these studies have employed paradigms that eliminate or minimize it, allowing direct comparison of adaptation under "hit" versus "miss" conditions. One such method is the *target jump* paradigm, in which the target is shifted mid-movement to align with the rotated cursor, ensuring task success and effectively eliminating task error (Al-Fawakhiri et al., 2023; Leow et al., 2018; Tsay et al., 2022). Using this approach, Leow et al. (2018) found that a removal of task error through target jumps resulted in a reduction of implicit adaptation by approximately 18% and total adaptation by approximately 50%. Similarly, Tsay et al. (2022) combined target jumps with an error-clamp paradigm and found a 13% reduction in implicit adaptation, measured by changes in hand angle, when task error was eliminated.

An alternative approach to reducing task error involves manipulating target size. Oversized or wide targets ensure that the cursor lands within the target region regardless of movement accuracy, thereby removing failure-related feedback (Al-Fawakhiri et al., 2023; Kim et al., 2019). Using this method, Kim et al. (2019) introduced graded task error conditions—ranging from complete misses to partial and full hits—and showed that larger targets (i.e., task success) led to approximately 35% less implicit adaptation during late learning phases compared to miss conditions.

To further investigate the role of task error in implicit motor adaptation, the present study employs a visuomotor reaching paradigm using Single Trial Learning (STL). This approach allows measurement of the immediate effects of learning by assessing reach aftereffects following individual training trials, where we randomly vary the magnitudes of visuomotor adaptation. The key manipulation involves modulating task error by varying target size: small targets introduce task failure when the rotated cursor misses the target, whereas wide targets minimize task error by ensuring success. By comparing aftereffects across these target conditions, the study aims to isolate the influence of task error on the earliest stages of implicit adaptation.

Methods

Participants

Seventy-four (74) participants from York University took part in the experiment (mean age = 20.12, SD = 3.02). All participants provided informed consent before beginning the study. All participation was voluntary, and participants were recruited through the Undergraduate Research Participant Pool (URPP) and the Kinesiology Undergraduate Research Experience (KURE). All participants reported having normal or corrected-to-normal vision. To examine initial implicit adaptation across a variety of rotations, thirty-one (31) of these participants were assigned to a group with 20 possible perturbations from ±1º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, 40º, and 45º, labelled as the 45º maximum rotation group, and fourty-three (43) of the participants were assigned to a group with 20 possible perturbations from ±1º, 5º, 10º, 15º, 20º, 25º, 30º, 40º, 50º, 60º, labelled as the 60º maximum rotation group. The second group was introduced later on in our study to address a different research question under investigation in our lab.

Experimental Set-Up

An illustration of the experimental apparatus is shown in Fig. 2. The experimental set up consisted of a DELL E2009W monitor (44.30 cm length, 24.89 cm height) that was placed face down on top of a metal frame (54 cm x 54 cm x 30 cm). Underneath the monitor, an upward-facing mirror (50 cm x 35 cm) was placed at a vertical distance of 29 cm from the monitor. A Wacom Intuos Pro Large drawing tablet (44 cm x 27 cm) was positioned 25 cm below the mirror where the participants completed the experiment by reaching towards targets. The mirror and positioning of the participants' hand beneath occluded the participants' view of their arm and hand, causing them to rely on proprioceptive feedback and the visual feedback displayed on the mirror.

A plastic stencil was placed on the tablet to restrict reaching movements to within 8.5 cm, which was the distance between targets and the home position, and an angular range of 10° to 170° in polar coordinates. This plastic stencil also created a cone shaped reaching area for the participants (Fig. 2A). The tip of the cone included the home position, and its main purpose was to funnel the return movements back to home position since the participants did not have visual feedback of neither their hand nor the cursor when returning to this home position. Thus, as illustrated in figure 3, home position (5 mm radius circle) was located at bottom of the reaching area, with targets located at a radial distance of 8 cm. Targets could be either white hollow dots (3 mm radius), located at either 60º, 75º, 90º, 105º, or 120º with respect to the home position, or a be centrally placed arc (5 mm thick), spanning from 30º to 150º. The cursor was a white filled circle of 3 mm radius.

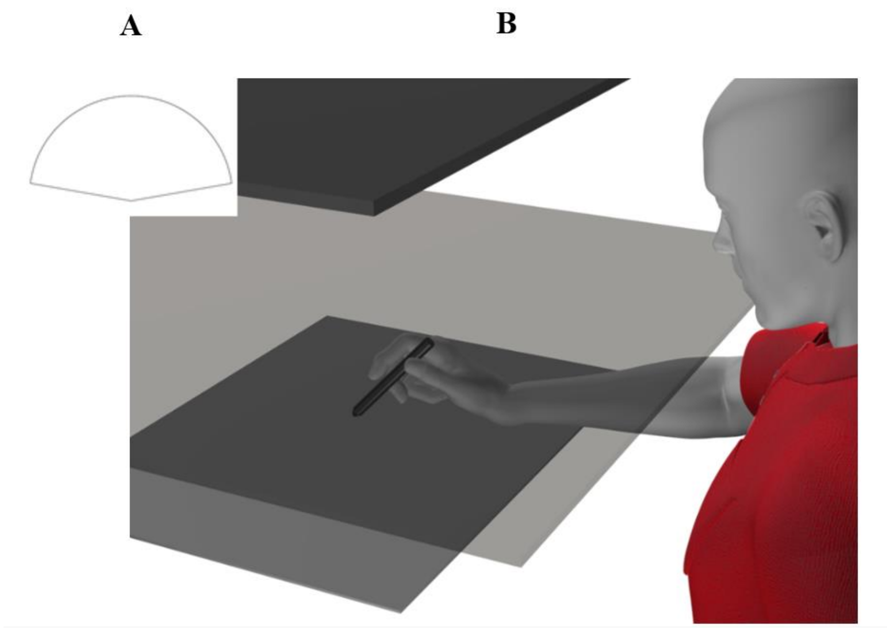

Fig. 2. Apparatus used by the participants to complete the experiment (B) and the tablet's cone-shaped opening where the participants completed the experiment's reaches (A). The stylus hovers over a digitized tablet during reaches, while the cursor's position projected on the monitor above is reflected off the mirror surface for participant viewing. Given the presence of mirror in between the monitor and the participant's hand, participant view of their hand is occluded.

Experimental Procedure

After answering the intake questionnaire, participants sat in front of the desk on which the apparatus was installed, and were instructed to look only at the mirror, reflecting the monitor, during the study. Trials began when the digitizing pen, and consequently the cursor, was held at the home position for 0.1 seconds. At this point, either the circular or arc-shaped target appeared. Participants were instructed to move the cursor, controlled by their unseen hand, directly towards the target until it reached the edge of the plastic stencil, representing the target's 8 cm radial distance. Once they moved the cursor/pen by this required radial distance, and thus completed the outward reach, the cursor and target remained visible for 0.6 seconds to make clear the size of the task error. Afterwards, the cursor and target disappeared, and participants returned the stylus, and therefore the cursor, to the home position to end the trial. A new trial began after holding the cursor at the home position for 0.1 seconds. To encourage consistent and accurate movements, a pleasant auditory tone was provided if movement onset occurred within 0.15 to 10 seconds, and the cursor's travel time from the home position to the stencil edge fell within 0.2 to 0.4 seconds. If these requirements were not met, a negative tone was provided instead, although all data was used for analysis.

In the initial familiarization, or “aligned-acquired” trials, which, as described later, were not included in the analyses, participants were required to move the aligned cursor towards the targets and to "hit", or partially overlap the cursor onto the target, to emphasize accuracy. For these trials, the pleasant tone was provided only if the cursor overlapped with the target within the 0.2 to 0.4 seconds time window. However, in the trials involving cursor rotation following familiarization, only completing the radial distance of the cursor was required for trial completion.

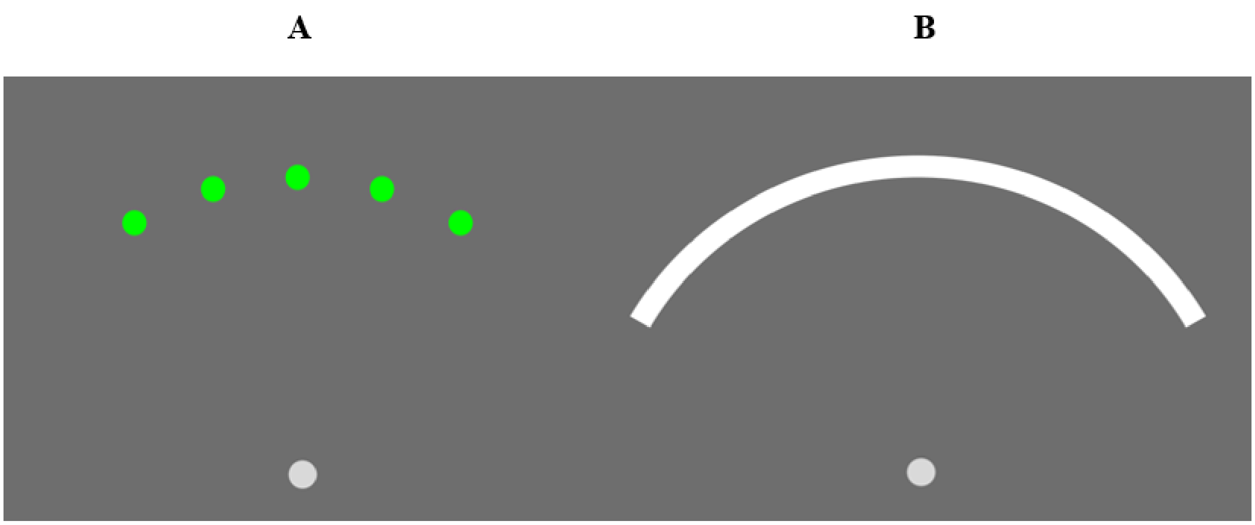

Fig. 3. Visual representation of all possible circular target locations at 60º, 75º, 90º, 105º, or 120º (A), and arc target spanning from 30º- 150º (B) in the experiment. All targets are located 8cm away from the home position represented with the grey circle, which was located along the body midline.

Types of Trials

As described earlier, two basic trial types were implemented in this study; aligned trials, and rotation trials. Aligned trials provided veridical cursor feedback to the participants, while rotation trials introduced rotated visual feedback of the cursor. Aligned-cursor trials required participants to reach for a circular target randomly positioned at one of the five locations shown in Fig. 3A. In contrast, rotated-cursor trials involved reaching either towards an arc-shaped target (Fig. 3B) or for the circular target located at the 90-degree position, represented by the middle target position on Fig. 3A. The direction and magnitude of the perturbation of the rotation trial was also pseudorandomized from a set of 20 rotations in the range of either ±1º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, 40º, and 45º (45º maximum rotation group) or ±1º, 5º, 10º, 15º, 20º, 25º, 30º, 40º, 50º, 60º (60º maximum rotation group), where the positive values represent clockwise rotations, and the negative values represent counterclockwise rotations.

Before the Single Trial Learning (STL) experimental trials, participants completed a series of aligned-cursor reaches for familiarization, as described earlier. In these trials, participants were required to ensure the aligned cursor partially overlapped with the target to successfully complete the trial. These aligned-acquire trials were not included in the data analysis but were designed to encourage participants to prioritize accuracy. Additional aligned-acquire trials were embedded throughout the main STL paradigm to maintain this focus on accuracy.

During the main paradigm, participants completed a series of 4, 5, or 6 trials, referred to as an STL bout. The structure of the trials in one STL bout has been illustrated on Fig. 4. In the first trial of each bout, the cursor motion was aligned with the hand, but the cursor was not required to overlap with the target. Instead, it simply needed to move a specific distance, corresponding to one of the five possible target locations shown in Fig. 3A. The purpose of this trial was to measure the participant's baseline performance before encountering a rotation trial, and therefore, we will label this trial as "Baseline" in our data analysis.

The second trial in an STL bout was a rotation trial, during which the cursor direction was misaligned relative to the unseen hand. Participants reached towards either circular or arc-shaped targets, and as previously described, successfully meeting the travel distance requirements resulted in target completion. These trials will be labelled as "Rotation" trials in our data analysis.

The third trial in an STL bout was identical to the "Baseline" trial, and was designed to measure the participants' latent learning after encountering a rotation. Therefore, we have labelled this third trial as "Aftereffects" in our data analysis. This was followed by 1, 2, or 3 additional trials designed to help eliminate any residual learning from the previous rotation. These trials, referred to as "Washout" trials, varied in number to make the rotation trial in the subsequent bout less predictable.

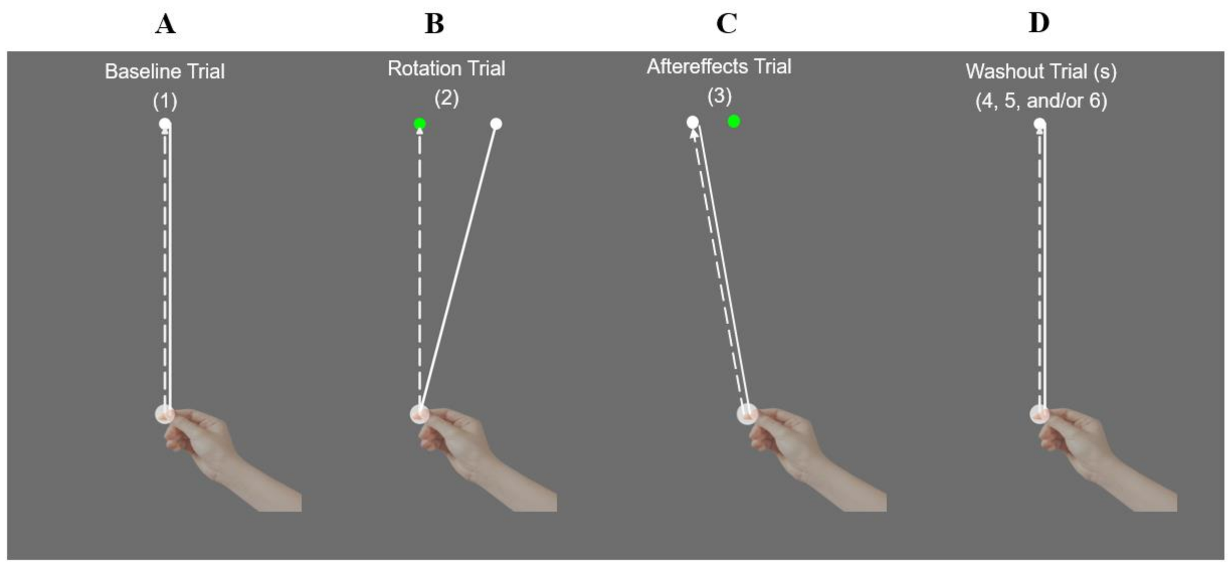

Fig. 4. Basic trial structure of one STL bout. The first four trials always follow the same pattern of (1) Baseline (fig. 4A), (2) Rotation (fig. 4B), (3) Aftereffects (fig. 4C), and (4) Washout (fig. 4D). However, some STL bouts may contain one or two additional Washout trials in order to minimize the possibility of participants predicting when a new Rotation trial will appear.

Experimental Schedule

An example permutation of the entire experiment for the 45º maximum rotation group is illustrated in Fig. 5. The experiment began with 80 familiarization trials, the first 40 of which involved reaching towards the dot shaped targets, followed by reaching towards the arc shaped target for the latter 40 trials. This familiarization phase is the portion of the plot to the left of the first vertical dashed line on Fig. 5. This was followed by an average of 1,200 reach trials, comprising approximately 240 STL bouts. Half of these bouts involved arc-shaped targets (indicated by yellow vertical lines on Fig. 5), while the other half featured circular or dot targets (represented by blue vertical lines on Fig. 5). The size and direction of the lines reflect the magnitude and direction of the rotation. Aligned-cursor trials, marked by a zero line to represent

0° rotation, appear as flat portions of Fig. 5. Thus, with an STL bout ranging from 4 to 6 trials, 20 rotations, 2 target types, and the requirement that each rotation be presented with each target type exactly 5 times, the experiment ensured balanced and systematic coverage of all conditions.

In order to insert breaks and some training with the Aligned-acquire trials, the STL bout were divided into 5 segments as indicated by the vertical dashed lines on Fig. 5. Each segment began with 10 aligned-acquire trials, followed by approximately 8 bouts (40 trials) of reaches that include an arc target for the training trials and 8 bouts involving the dot target as illustrated in Fig. 5.

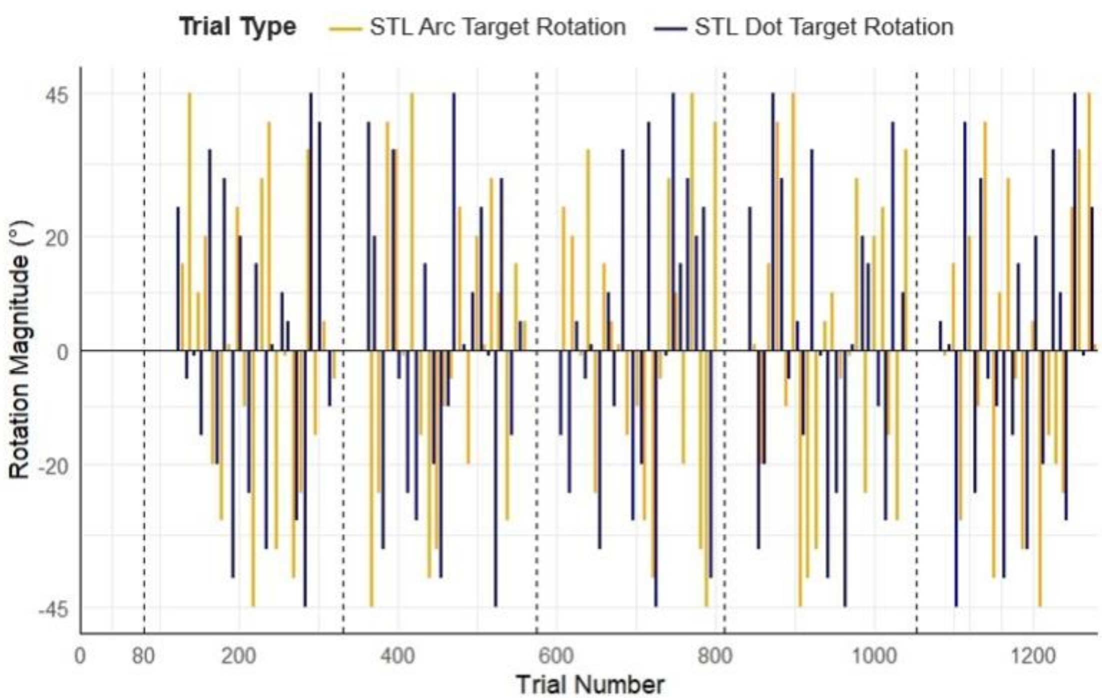

Fig. 5. An example of one perturbation schedule for the entire experiment for the 45º maximum rotation group. The Familiarization phase (trials 0 – 80), consists of 40 familiarization trials with the circular target, followed by another 40 trials with the arc target. The STL phase (trials 81 – 1282 in the above example), consists of approximately 1200 trials. STL bouts are made up of 1 baseline, 1 rotation, 1 aftereffects, and 1, 2, or 3 washout trials. The rotation values are pseudorandomized from bout to bout, and have 20 possible values from ±1º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, 40º, 45º, as depicted in this figure, or ±1º, 5º, 10º, 15º, 20º, 25º, 30º, 40º, 50º, 60º. The vertical dashed lines mark 1-minute breaks, which occurred approximately every 200 trials in the STL phase. A series of 10 aligned-acquire trials were incorporated after each break prior to the re-start of the STL bout series.

In the rotation trials, the purpose of using the dot and arc targets was to manipulate task error. Given that the rotation of the cursor motion was randomized, participants nearly always missed the targets when it was a circular target as illustrated in Fig. 6A. The arc target was wide, and therefore, even with large rotations, the cursor would have a high chance of intersecting this target as in Fig. 6B. This led to the very low likelihood of task error when reaching towards the arc targets, while maintaining task error for the circular targets. Due to the presence of cursor rotation, sensory prediction error was present when reaching towards both circular and arc-shaped targets. The difference between trials before and after a single rotation trial was used to evaluate the extent of implicit adaptation to that rotation. By analyzing these differences based on target type, we can assess the extent to which target errors contributed to initial implicit adaptation. Additionally, comparing these differences as a function of rotation magnitude allowed us to further examine the impact of rotation size on adaptation.

Note that because our array of rotations includes values as small as 1º, it is unlikely that these would result in task errors for the dot target, which has a radius of approximately 2.15º, as it would for larger rotation. At such small rotation magnitudes, the cursor would still fall within or very close to the target, minimizing the likelihood of a miss. Therefore, we do not expect differences between target types at this rotation size.

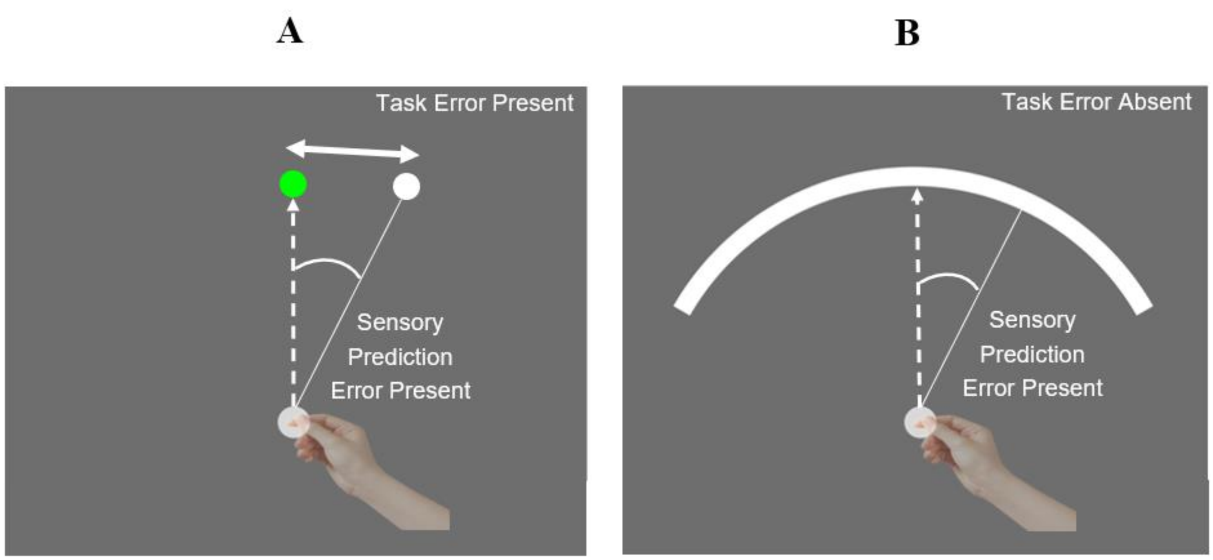

Fig. 6. Visual representation of how both sensory prediction error and task error are present when reaching towards circular targets on Rotation trials (A), whereas the arc targets (B) greatly reduce the likelihood of task error by providing a broad region for successful hits. The hand used for making reaches is occluded throughout the duration of the experiment. The dashed line represents hand trajectory and the solid line represents cursor's trajectory.

Data Analysis

To obtain initial changes in implicit adaptation, we looked at trial-by-trial changes in angular reach deviations between baseline and aftereffects trials within each STL bout. We implemented this since these trials, as described earlier, were identical in terms of their targets and criteria for successful target reach completion. The baseline trial was always prior to the rotation trial where participants faced cursor rotations, and the aftereffects trial was presented after the rotation trial, allowing us to get a reasonable estimation of implicit learning due to the rotation trial through the comparison of performance across these 2 trials.

Data preprocessing initially occurred during the experiment, where the program itself calculated participant reach deviations. In each trial, once the cursor was moved by 2cm or more from the home position, the experiment recorded the cursor's position and calculated a reach direction relative to the target's location in degrees, providing us with angular reach deviation measures. This 2cm cursor landmark was selected since it is at 1/4 of the distance between the home position and the targets (8cm), which is prior to when most participants reach peak movement velocity at 1/3 of the home-target distance and start making hand adjustments. Initial implicit learning change was calculated by subtracting the baseline trial deviation from the aftereffects trial deviation within each STL bout. The rotation values from every rotation trial in a participant's STL phase were then extracted. Reach deviations exceeding -45º and 45º (for the 45º maximum rotation group) and -60º and 60º (for the 60º maximum rotation group) were removed as outlier data, as these values fall outside the range of cursor rotations incorporated in our study and therefore, the maximum theoretical deviations of participants. Finally, the reach data were collapsed across positive and negative rotations, normalized to allow their visualization on a positive scale, and averaged across rotation size. To answer the research question, we performed a 2x10 repeated measures ANOVA on initial implicit reach deviations using target type (circular target or arc target) and rotation size (1º, 5º, 10º, 15º, 20º, 25º, 30º, 35º, 40º, 45º or 1º, 5º, 10º, 15º, 20º, 25º, 30º, 40º, 50º, 60º) as within-subject predictor variables for each group. The groups were not compared to each other. These analyses were conducted using R (https://www.r-project.org/).

Results

To examine the effect of task error on initial rates of implicit adaptation, 31 and 43 participants completed a Single Trial Learning (STL) paradigm with trials incorporating 20 pseudorandomized cursor rotations with maximum rotations of 45º and 60º, respectively. After calculating the trial-by-trial changes in angular reach deviations between baseline and aftereffects trials within each STL bout and removing outliers, the responses were collapsed across positive and negative rotations, as demonstrated in Fig. 7. The median reach deviation was then taken within each participant, and a 95% confidence interval of the mean across participants' median reach deviations was bootstrapped.

Impact of Task Error on Initial Implicit Adaptation

As can been seen in Fig.7, reach aftereffects emerged following training with both small dot targets and large arc targets, as indicated by the confidence intervals lying above the zero-error line. As illustrated by the blue lines in Fig. 7, reach aftereffects following dot target training were 1º - 2º larger than those observed with the wide arc target in the 45º maximum rotation group (Fig. 7A and 8A) [$F (1, 30) = 11.52$, $p = 0.002$, $\eta^2g = 0.027$] and 60º maximum rotation group (Fig. 7B and 8B) [$F (1, 42) = 66.24$, $p < .001$, $\eta^2g = 0.103$]. For reasons that are unclear and were not tested—since we had no prior expectation—it appears that the difference between target types was slightly larger in the groups with the larger maximum rotations (i.e., 60º maximum rotation group). Nonetheless, the overall main effect of target type in both groups, suggests that the additional target error signals produced after training with the dot target leads to larger initial implicit change compared to when only sensory prediction error was available, as was the case for trials involving reaches to the arc.

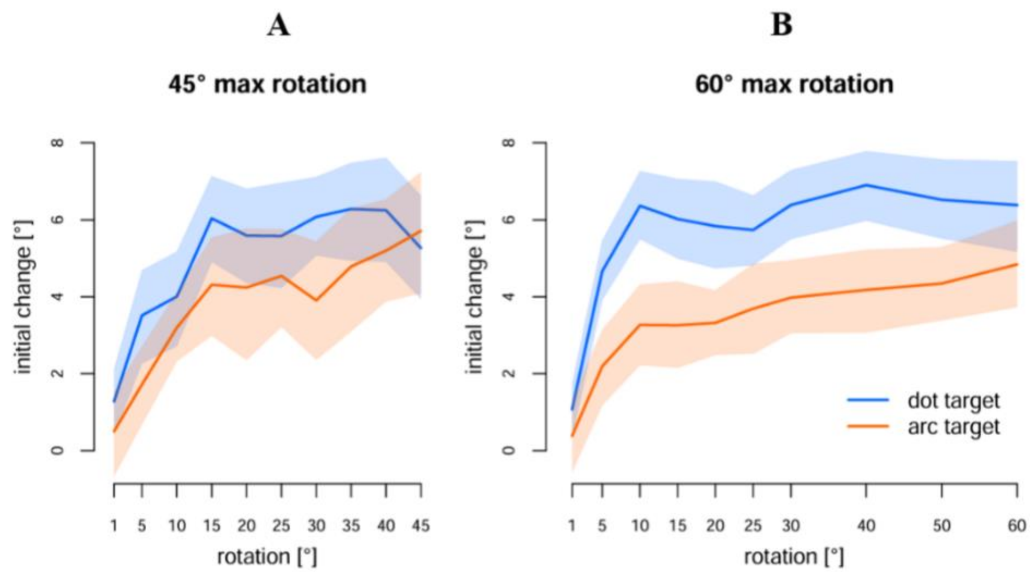

Fig. 7. Initial changes in implicit learning, as measured by reach aftereffects, for the participant group with 45° maximum rotation (A) and 60° maximum rotation (B). Blue line represents the average reach aftereffects for trials following reaches to the dot target, and orange line represents those involving reaches to the arc shaped target, for the different rotation magnitudes. 95% confidence intervals are bootstrapped across the reach aftereffects data for both the dot and arc target reaches.

Not surprisingly, the size of the rotation also had an effect on initial implicit changes for both the 45º maximum rotation group [$F (5.83, 174.81) = 13.91$, $p < 0.001$, $\eta^2 g = 0.151$] and 60º maximum rotation group [$F (6.84, 287.36) = 19.95$, $p < 0.001$, $\eta^2 g = 0.149$]. Initial reach deviations gradually increased for smaller rotations of 5°-10°, averaging at approximately 3.6°, but remained stable at approximately 6° for larger rotations of 15º-90º.

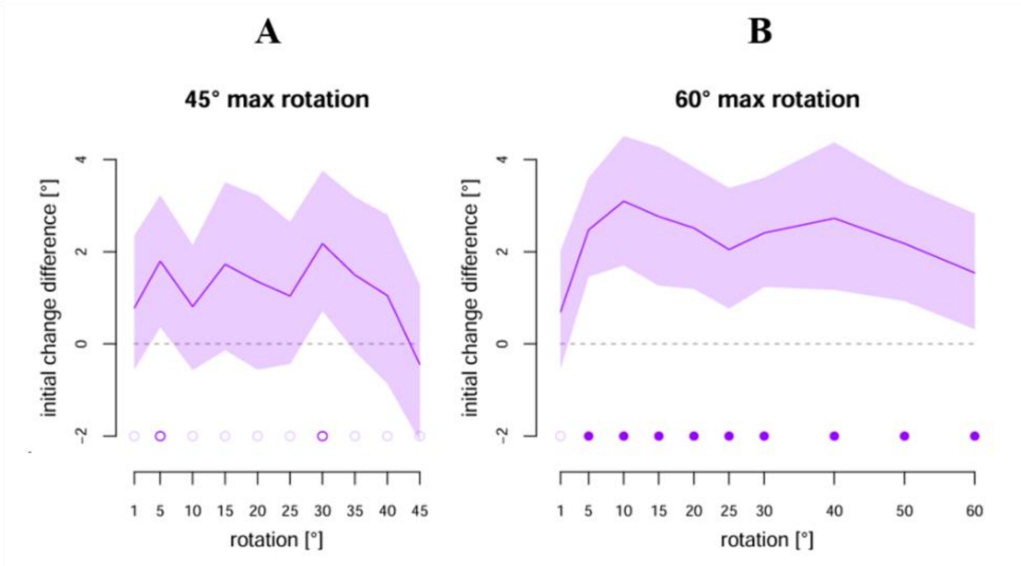

Fig. 8. Difference in initial implicit learning between dot and arc targets, , calculated as the difference in reach aftereffects for the two target types, shown for the 45° (A) and 60° (B) maximum rotation groups as a function of rotation magnitude on the training trial. Each circle represents a t-test comparing aftereffects across target types at a given rotation magnitude: light purple hollow circles indicate non-significant results, dark purple hollow circles indicate significant results ($p < 0.05$), and dark purple filled circles indicate significance after false discovery rate correction.

However, this main effect of rotation size did not interact with the target type for either the 45º nor the 60º maximum rotation group ($p = 0.504$ and $p = 0.370$, respectively). The absence of a significant interaction suggests that the larger initial aftereffects following the small dot target were generally consistent across all rotation values. The absence of an interaction is somewhat surprising since we see no difference for the smallest rotation (1º), where no difference was observed, as we expected, because the width of the dot target spanned approximately 4.3º, making task errors unlikely on average. Nevertheless, Figure 8 does indicate some variation in the magnitude of this difference as a function of rotation size. For the 45° maximum rotation group, reach aftereffect differences between the two target types were only significant at 5° and 30° rotations, as denoted by the dark purple hollow circles. In contrast, the effect of target type was more pronounced in the 60° group, where the differences in reach aftereffects reached statistical significance at all rotation values beyond 1°, based on t-test comparisons corrected for false discovery rate. Both the persistence of target-type differences in the 60º maximum rotation group and the marginal, non-sequential differences in the 45º maximum rotation group are consistent with the absence of a significant interaction between target type and rotation size. These findings suggest that while the overall pattern of greater aftereffects for the dot target is consistent (which include target error along with sensory prediction error), the strength of this effect becomes more apparent in the group who trained with higher rotation magnitudes.

To demonstrate that the small difference in initial aftereffects between the two target types was consistent across participants, Figure 9 presents scatterplots of the averaged aftereffects following training with the dot target (y-axis) plotted against those following training with the arc target (x-axis) for each participant in the 45° (Fig. 9A) and 60° (Fig. 9B) maximum rotation groups. As consistent with the group-level results reported above, most participants showed larger initial aftereffects after training with the dot target, which involved both prediction error and task error, compared to training with the arc target, which primarily involved prediction error alone. Accordingly, most data points fall above the unity line in both scatterplots. The corresponding adjusted R^2 values are 0.23 and 0.16, indicating a modest positive relationship between aftereffects across target types. This suggests that participants who showed larger initial aftereffects for one target type tended to do so for the other as well—possibly reflecting a shared underlying influence, such as the common sensory prediction error signal.

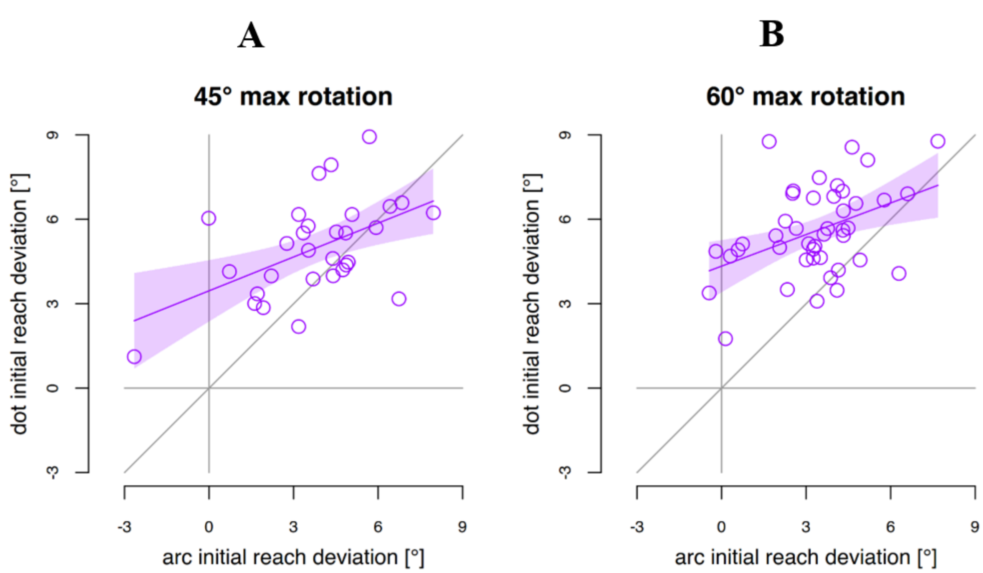

Fig. 9. Averaged initial implicit learning for each participant (circles) when reaching to dot versus arc targets, shown separately for the 45º (A) and 60º (B) maximum rotation groups. The purple line represents the line of best fit, and the black diagonal line indicates the unity line (slope = 1).

Discussion

While implicit adaptation has traditionally been assumed to rely primarily on sensory prediction errors, our study aimed to examine whether task errors also contribute to the development of implicit adaptation across various cursor perturbations in a Single Trial Learning (STL) visuomotor reaching experiment. We measured initial rates of implicit adaptation, by measuring reach aftereffects that follow every single training trial with a misaligned cursor of different magnitudes, and comparing these aftereffects following the training trials. Task error was removed, or the likelihood of its presence was at least greatly reduced, through enlarging the target size so that the cursor should intersect an arc shaped target the single training trials regardless of the size of the cursor rotation. Our study showed that task error, in combination with sensory prediction error, can contribute to greater implicit adaptation as measured through initial reach aftereffects, and this effect was shown to be consistent across different cursor rotations.

Our findings indicate that the presence of task error when reaching toward small dot targets was indeed associated with larger aftereffects, and therefore, greater implicit learning, compared to reaching towards arc shaped targets where task error was unlikely (as shown in Fig 7). Because sensory prediction error was present in both dot and arc target conditions—due to the imposed cursor rotations—any additional increase in aftereffects for the dot target can be attributed to the presence of task error. In our study, initial reach aftereffects were on average 1º - 2º greater for dot target reaches compared to arc target reaches in both the 45º and 60º maximum rotation groups, corresponding to approximately 10-20% greater initial rates of implicit learning on the dot target compared to the arc target in both groups. Previous literature has shown the incorporation of task error to be associated with larger overall implicit learning reach aftereffects by 1º to 5º on average, produced after extensive training with hundreds of trials (Al-Fawakhiri et al., 2023; Leow et al., 2018; Tsay et al., 2021; Tsay et al; 2022). In studies incorporating the error-clamp paradigm, the removal of task error led to approximately 5.7º to 10º less adaptation as measured by changes in hand angle (Kim et al., 2019; Leow et al; 2020), corresponding to the attenuation of implicit recalibration anywhere from 13% to 35% (Al Fawakhiri et al., 2023; Kim et al., 2019; Tsay et al., 2022) and overall adaptation anywhere from 30% to approximately 50% (Leow et al., 2018; Leow et al., 2020). In our study, the initial reach aftereffects similarly increased for both the 45º and 60º maximum rotation groups when training included consistent task error. Our findings suggest that the presence of task error enhances implicit learning from the very beginning of adaptation—

highlighting that task error exerts an immediate effect on the extent of implicit recalibration, regardless of the magnitude of maximum rotation experienced.

Our results replicate a well-established pattern in the visuomotor adaptation literature where implicit system shows a rapid increase in adaptation for small errors, followed by a plateau at larger rotation sizes. This sublinear pattern—previously observed in studies that measured aftereffects only after many training trials (e.g., Bond & Taylor, 2015; Morehead et al., 2017; Kim et al., 2018; Leow et al., 2017; Tsay et al., 2021)—also emerged in our data after just a single training trial (for each STL bout). Specifically, for both the 45º and 60º maximum rotation groups, reach aftereffects following rotated-cursor reaches to the small dot target increased gradually for rotation sizes between 1º and 10º, averaging at 3.6º, but then leveled off at 6º for larger perturbations of beyond 15º. Importantly, this capped pattern was evident even in the arc target condition, where task error was minimized, and only sensory prediction error was present. This confirms that the saturation of implicit adaptation at higher rotation magnitudes does not depend on task error and likely reflects a general limit in how the motor system processes large sensory discrepancies. By demonstrating this effect under conditions of minimal task error and brief exposure, our findings suggest that the characteristic nonlinearity of implicit adaptation emerges early in learning and is a fundamental feature of the system.

Interestingly, this additive effect of task error remained relatively stable across rotation sizes. Despite variability in the magnitude of the imposed perturbations, the difference in aftereffects between dot and arc targets did not significantly interact with rotation size. This suggests that task error enhances implicit adaptation in a largely uniform manner, rather than scaling proportionally with the size of the error. The consistency of this effect—even when the absolute amount of adaptation begins to plateau—points to task error acting as a fixed boost to the learning process, rather than amplifying sensitivity to error magnitude. Notably, the only exception was at the smallest rotation (1º), where task error was unlikely and no reliable difference between target types was observed. While our work is one of the first studies to examine the influence of task error on implicit adaptation across a wide variety of cursor rotations, other studies incorporating fewer cursor rotations also underscore the uniformity of task error's contribution to implicit adaptation regardless of cursor rotation (Bond & Taylor, 2015; Leow et al., 2017; Leow et al., 2018), although the direction of rotation may have some contribution to the extent of implicit adaptation (Leow et al., 2017). Similarly, studies incorporating the error-clamp paradigm have found a lack of implicit adaptation scaling up with task error over time for a variety of error clamp sizes (Morehead et al., 2015; Morehead et al., 2017; Kim et al., 2018; Kim et al., 2019; Tsay et al., 2021).

It is important to note that we measured the influence of task error on implicit adaptation with respect to the absolute magnitude of change in reach aftereffects. If we were to instead consider relative change—that is, the size of the aftereffect expressed as a percentage of the imposed rotation—it becomes clear that this percentage decreases as rotation magnitude increases. For example, a 5° aftereffect represents a substantial proportion of a 15° rotation but only a small fraction of a 45° or 60° rotation. This declining proportion at larger errors suggests that while the motor system continues to register and adapt to errors, its sensitivity to the magnitude of those errors diminishes, leading to a plateau in relative implicit learning. Thus, although task error enhances the absolute amount of learning, its effect becomes proportionally less impactful as the overall perturbation grows. This further supports the idea that implicit adaptation has a saturating response to error and that task error acts more like a fixed boost rather than a scaling factor.

To further explore the effect of task error on implicit learning, future studies can incorporate alternative manipulations of task error. For example, expanding on Al-Fawakhiri et al.'s (2023) findings on target jump being more effective than target size manipulations in suppressing implicit adaptation, a similar study can be conducted where target jumps are incorporated shortly after the beginning of each trial for task error removal instead of the arc target. Comparing the effectiveness of target size and target jump in terms of task error manipulation and its subsequent impact on implicit adaptation can subsequently be used to develop more effective rehabilitation and motor learning programming.

In most models of motor learning, task error—the failure to achieve the movement goal—has been assumed to primarily drive explicit strategy use, prompting conscious corrections in response to visible performance errors. In contrast, implicit adaptation has been characterized as an automatic process governed solely by discrepancies between predicted and actual sensory feedback. However, the current results suggest that task error can modulate implicit learning even at its earliest stages, as evidenced by larger aftereffects following training with the small dot target, where missing the target was more likely. That task error enhanced reach aftereffects—even when measured immediately after a single exposure—argues for a more flexible and context-sensitive view of implicit adaptation than previously thought.

Conclusion

The present study has shown that task error, when combined with sensory prediction error, as occurs when reaching towards dot targets, can enhance implicit adaptation, even after a single exposure and across a range of rotation magnitude By showing that implicit adaptation is modulated by task success (hit) or failure (miss), this work supports emerging models that incorporate multiple sources of error in motor learning. Beyond advancing theoretical understanding, these insights have practical implications for optimizing learning in applied domains such as rehabilitation, sport, and skills training, where structured exposure to both task and prediction errors may enhance motor performance and recovery.

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