Title: A spatial explicit strategy reduces error but interferes with sensorimotor adaptation

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Abstract

Although sensorimotor adaptation is typically thought of as an implicit form of learning, it has been shown that participants who gain explicit awareness of the nature of the perturbation during adaptation exhibit more learning than those that do not. With rare exceptions, however, explicit awareness is typically polled at the end of the study. Here, we provided participants with either an explicit spatial strategy or no instructions prior to learning. Early in learning, explicit instructions greatly reduced movement errors but also resulted in increased trial-to-trial variability and longer reaction times. Late in adaptation, performance was indistinguishable between the explicit and implicit groups, but the mechanisms underlying performance improvements remained fundamentally different, as revealed by catch trials. The progression of implicit recalibration in the explicit group was modulated by the use of an explicit strategy: these participants showed a lower level of recalibration as well as decreased after-effects. This phenomenon may be due to the reduced magnitude of errors made to the target during adaptation, or inhibition of implicit learning mechanisms by explicit processing.

Keywords: implicit, visuomotor, reaching, recalibration, catch trials, error
Introduction

While explicit instruction is routinely used in sports and rehabilitation settings, surprisingly little is known about how it affects motor learning processes. Explicit knowledge is associated with faster learning of a visuomotor transformation (Werner and Bock 2007) and with superior performance of motor sequences (Willingham et al. 2002). Providing participants with an explicit strategy speeds their adaptation to walking on a split-belt treadmill (Malone and Bastian 2010).

But there is a tradeoff: applying strategies during execution of well-practiced movements hurts performance (Beilock and Carr 2001; Beilock et al. 2002; Castaneda and Gray 2007; Flegal and Anderson 2008; Perkins-Ceccato et al. 2003; Poolton et al. 2006; Zachry et al. 2005). Strategies can even negatively affect learning of some tasks, such as balancing on a stabilometer (Wulf et al. 2001). These effects are hypothesized to result from increased cognitive load interfering with automatic motor control processes (Masters et al. 2008; Willingham 1998).

While adaptation relies on cognitive processes such as spatial working memory (Anguera et al. 2010), this does not necessitate explicit awareness (Galea et al. 2010).

As motor learning progresses, there is a shift towards more automatic control that appears to be obligatory (Mazzoni and Krakauer 2006; Willingham et al. 2002). However, traces of explicit processes persist well after performance has plateaued during motor sequence learning (Willingham et al. 2002). Whether implicit and explicit processes interact in visuomotor adaptive learning is unclear. Visuomotor adaptation often happens implicitly, without our attending to it, such as when we adjust our movements to the settings of a mouse on an unfamiliar computer. However, some visuomotor transformations, such as learning how far to turn the wheel while parallel parking a new car, are learned using conscious strategies or under
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explicit instruction. Whether such explicit instruction can enhance adaptive recalibration, or
whether such control is completely overridden by implicit processes, is still a matter of debate
(Arce et al. 2009; Cameron et al. 2010a; b; Hegele and Heuer 2010; Mazzoni and Krakauer
2006; Pisella et al. 2004; Sulzenbruck and Heuer 2009; Werner and Bock 2007). The amount of
rest between trials, in which explicit strategies may be integrated with procedural knowledge,
may modulate explicit facilitation of learning and explain these differing results.

In the present study, we hypothesized that explicit instruction would facilitate visuomotor
adaptation, particularly when participants were given longer rest breaks. We also implemented
catch trials to probe the progression of implicit recalibration when participants were provided
with explicit task instructions.

Materials and Methods

Participants

54 adults (ages 18-25, 28 females and 24 males) participated in the experiment. They
signed an institutional review board-approved consent form and were granted credit towards an
introductory psychology class as compensation. Participants were randomly assigned into one of
two groups: an implicit learning group or an explicitly-instructed group. These groups were then
further parsed into subgroups where participants were given either 1s or 7s of inter-trial rest (1-ITR and 7-ITR). An equal distribution of gender was maintained across all subgroups.

Procedure

Participants sat upright in front of a computer monitor and, using the dominant right
hand, performed a visuomotor adaptation task, controlling a cursor by moving a Logitech
Extreme 3D joystick (Fremont, CA). The joystick position was sampled at a rate of 250Hz.
Targets were displayed in the four cardinal directions in a random order and were displayed for
750ms. Targets were 92mm away from the center of the screen and required a 35mm hand movement (measured at the thumb). Participants were instructed to move as quickly and accurately as possible to the target and to hold the cursor in the target until it disappeared. They did not guide the return movement, but rather were instructed to release the joystick momentarily to return the cursor to the center. The delay between target presentations was 750ms. Trials were presented in blocks of eight, in between which were the 1s or 7s rest breaks.

**Block Design**

**Baseline.** Participants were first presented with nine baseline blocks with veridical visual feedback.

**Non-Vision.** After the baseline period, participants completed two blocks of trials with no visual feedback of the joystick motion.

**Rest Period and Instructions.** After the non-vision blocks and before the first adaptation block, both groups took a three minute break.

**Explicit participants.**

During this three minute break, explicit participants were shown a clock face (Figure 1) and were told that their movement feedback would be rotated by 30° about the central target location. They were then shown that if they pushed towards 12 o’clock, the cursor would move to 1 o’clock, so therefore if they wanted the cursor to move towards 12 o’clock, they would have to push towards 11 o’clock. This was repeated for the other three targets at the 3 o’clock, 6 o’clock, and 9 o’clock directions.

Explicit participants were also advised that periodically throughout the adaptation period, there would be blocks of single trials with no feedback and no rotation (catch trials, described in
greater detail below). They were told not to use their strategy on these blocks and were reminded of this at regular intervals throughout adaptation.

**Implicit participants.** During the three minute break, implicit participants simply rested. They were informed that periodically throughout the adaptation period, there would be blocks of single trials with no feedback. They were told to hit the target just the same, and to make their best guess as to how far to move the joystick to land in the target’s center.

**Adaptation.** After the rest break, both groups completed 38 blocks of 8 trials each, or 304 total trials, under the 30° clockwise rotated feedback. Participants were told when this period of the study was ¼, ½, and ¾ complete. No breaks were given other than the inter-trial rest.

**Catch Trials.** During adaptation, after every two blocks of eight trials, participants completed one trial with no visual feedback (a catch trial). Explicit participants were informed via text on the computer screen that the rotation had been turned off, and that there would be no feedback on this trial. They were also reminded to turn their strategy off, aiming straight to the target. Implicit participants did not receive further reminders during the adaptation period, though they were informed via an instructional screen that there would be no feedback on the upcoming trial.

**Washout.** Immediately after the adaptation blocks, participants then performed twelve blocks of trials with veridical visual feedback in order to assess after-effects. Note that explicit learners were informed prior to these blocks that the rotation had been removed, and were advised to stop using their strategy.

**Polling.** After the task was complete, participants in the implicit group were polled for strategy use or explicit awareness using a flow chart, shown in Figure 2. Participants whose
responses followed the path of the bold grey lines at left demonstrated clear explicit awareness and strategy use. Participants claiming use of a rotation-based strategy were likewise considered to have used a strategy and were excluded from further analyses. Explicit awareness was also attributed to those participants who reported noticing a disturbance in the intended cursor trajectory and subsequently characterized the disturbance as a rotation.

*Figure 2 here.*

**Data Analysis**

Joystick trajectories were filtered forwards and backwards using a second-order low-pass 10 Hz Butterworth filter. Reaction times (RT) were determined as the time when velocity reached 5% of the peak velocity during the first ballistic movement (Teasdale et al. 1993). Direction error (DE), the angle between a straight line from the start location to the target and the direction of actual movement, was determined at the time of peak velocity. Performance in both adaptation and washout was modeled by fitting exponential functions to trial-by-trial data. These functions have an intercept and a decay constant, which we calculated for each participant to evaluate their adaptation. This has previously been shown to characterize adaptation learning curves better than the power model (Heathcote et al. 2000). The effects of the instructions and rest breaks were then analyzed with an ANOVA as between-subjects factors. Following statistical tests (see Results) indicating neither a main effect of the rest break period, nor any interaction with instruction, the 1- and 7-ITR groups were pooled together. Differences between the explicit and implicit instruction groups in model parameters were then analyzed using independent-samples t-tests. A repeated measures ANOVA was used for analysis of the catch trials to assess the influence of instruction.

**Results**
Participants (2 from 1-ITR and 1 from 7-ITR) in the implicit groups who reported strategy use or explicit awareness at the end of the study were removed from further analyses. Two explicit participants were removed for not following instructions. Half of the participants in each instruction group had one-second inter-trial rest periods (1-ITR), and half had seven second rest periods (7-ITR). In adaptation, we found no main effect of rest period duration on model decay constant, $F(2,43)=0.41$, $p>0.5$, or model intercept, $F(2,43)=0.26$, $p>0.6$; there was also no interaction between rest period and instruction on decay constant, $F(2,43)=0.06$, $p>0.9$, or intercept, $F(2,43)<0.01$, $p>0.9$. We therefore pooled the 1- and 7-ITR groups together for all subsequent analyses.

Figure 3 here

Explicit participants exhibited better performance early in adaptation than implicit participants.

Explicitly-instructed participants were slower to react than implicit participants early in adaptation.
Mean RT during adaptation for both groups is displayed in Figure 3B. Explicit participants exhibited larger model intercept values than implicit participants (540ms for explicit vs. 372ms for implicit, \( t(1,46)=6.42, p<0.001 \)). Accordingly, explicit participants had a more negative time constant for RT improvement across adaptation than did implicit participants, \( t(1,46)=6.50, p<0.001 \). Bands indicate 99% confidence intervals of model-generated estimates of mean RT on each trial.

Performance was more variable under explicit than implicit conditions.

Mean standard deviation (SD) of DE on each block of trials for both groups is displayed in Figure 3C. Improvement in SD was also analyzed using an exponential model. Explicit participants exhibited a significantly larger intercept of this model than did implicit participants (21° vs. 10°, \( t(1,46)=10.76, p<0.001 \)). As with RT, explicit participants also had a stronger effect of time than implicit participants, \( t(1,46)=11.43, p<0.001 \).

Explicit participants had smaller after-effects than implicit participants.

DE during washout for both groups is plotted by trial in Figure 3A. Explicit participants had smaller DE model intercepts during washout than implicit participants (20° vs. 30°, \( t(1,46)=6.00, p<0.001 \)). As with DE in adaptation, implicit participants showed the strongest improvement with time, \( t(1,46)=5.65, p<0.001 \).

Explicit participants were slightly slower to respond than implicit participants during washout.
RT during washout for both groups is plotted by trial in Figure 3B. There was a significant difference in RT model intercept between explicit and implicit participants, \(t(1,46)=2.07, p<0.05\), but the absolute difference was small (379 ms for explicit vs. 339 ms for implicit).

\textit{Figure 5 here.}

**Implicit participants made larger errors during catch trials than explicit participants.**

Mean DE on catch trials for both groups are shown in Figure 5A. Catch trial DE was not analyzed using an exponential model, because catch trials did not start until after 16 trials of adaptation. Explicitly-instructed participants had lower mean DE during catch trials than implicit participants, \(F(1,46)=42.4, p<0.001\) (main effect of instruction on catch trials).

**Explicit and implicit participants did not exhibit different RT during catch trials.**

Mean RT for catch trial movements for both groups are shown in Figure 5B. Catch trial RT was not analyzed using a model, since RT was stable across the adaptation period. There was no main effect of instruction on RT during catch trials, \(F(1,46)=1.55, p>0.2\).

**RT did not predict DE on catch trials for explicit participants.**

A scatter plot of DE and RT for all catch trials for the explicit participants is shown in Figure 5C. There was no correlation between DE and RT on catch trials, \(R^2=0.0045\), \(F(1,411)=1.87, p>0.15\).
Inter-trial movement variability in early adaptation in explicitly-instructed participants did not correlate with the amount of recalibration. The relationship between the inter-trial movement variability and amount of recalibration in explicit participants was not significant, $R^2=0.0039$, $F(1,21)=0.008$, $p>0.9$.

RT in early adaptation in explicitly-instructed participants and recalibration.

Given the large increase in RT for explicit participants, we tested for a relationship between the RT early in adaptation and the subsequent amount of recalibration. This correlation trended towards significance with higher RT indicating more recalibration, $R^2=0.14$, $F(1,21)=3.42$, $p=0.079$.

Error magnitude in early adaptation in explicitly-instructed participants predicted the amount of recalibration.

A scatter plot of the DE exponential model intercept at washout vs. adaptation for explicit participants is shown in Figure 6. The amount of error experienced early in adaptation, as indicated by the adaptation model intercept, predicted the amount of recalibration, as indicated by the washout model intercept, $R^2=0.33$, $F(1,21)=10.25$, $p<0.01$.

Discussion

Explicitly-instructed participants exhibited a clear performance advantage over implicit participants in terms of accuracy during adaptation, as has been shown recently for adaptation to split-belt treadmill walking (Malone & Bastian, 2010). However, performance for explicit
participants was much less precise, as evidenced by the variability of their movement direction across trials. Despite the application of an explicit strategy, implicit recalibration still occurred in participants given explicit instructions as evidenced by catch trial performance and measureable after effects. However, explicitly-instructed participants recalibrated less than implicit participants, showing that the application of the strategy interfered with recalibration processes in a fashion consistent with previous work on prism adaptation (Jakobson and Goodale 1989). Moreover, explicitly-instructed participants responded more slowly during the early adaptation period.

**Reaction Time Effects**

Although explicitly-instructed participants were more accurate at moving to the targets than uninstructed (implicit) participants, their reaction times were slowed early in learning. At first glance, it seems that recalibration is necessary for efficient movement to occur, because the reduction in explicit participants’ RT mirrors their increase in catch trial error, and these two measures stabilize over about the same time period. Further, high RT early in learning trended towards predicting more recalibration. However, this is related not to explicit control itself, but the ability of the individual participant to apply the strategy. Participants who were able to effectively and quickly apply the strategy showed little or no recalibration. Thus, while the reduction in RT seen in some participants may reflect takeover by an implicit process, it is also possible for a participant using an explicit strategy to respond in the same timeframe as a participant who has adapted using purely implicit means.

We propose that the increased reaction time present in early learning for explicit learners is a result of an increased cognitive load due to application of a conscious strategy. Explicit
learning is therefore likely to be more sensitive to disruption by a secondary task (Galea et al. 2010; Taylor and Thoroughman 2007; 2008). We predicted that providing participants with longer rest breaks would allow them to better develop and employ their explicit strategy, but we did not observe any difference between the 1- and 7-ITR groups. This point should be explored further, as the schedule of interspersed catch trials may have allowed participants in the 1-ITR group enough extra time to obscure an effect of rest break duration. Future experiments using a constant response-to-stimulus interval in order to more precisely control the amount of processing time between trials, coupled with a finer scale of ITIs, may resolve this issue. Although RT was equivalent for the two groups by late adaptation, the fact that the adaptation is still (partially or completely) under explicit control may render performance more susceptible to interference during this period as well. This remains to be tested, but could help explain a number of phenomena, including the demonstrated negative effects of distracters on driving (Chaparro et al. 2005; Hahn et al. 2010; Wester et al. 2008), a task learned with explicit instruction.

Error Effects

Mazzoni and Krakauer (2006) demonstrated that while movements were initially accurate to the target when participants were explicitly instructed how to correct for a perturbation, implicit recalibration occurred unhindered. They concluded that the motor system recalibrates its output on the basis of a mismatch between the actual trajectories and the predictions of a forward model, in line with Kawato’s (1999) proposal. However, an important methodological difference between their study and ours was that they presented all possible targets on the screen at once. Participants were instructed to counter the rotation by aiming at the target directly
adjacent to the intended target. Under these conditions, adaptation might progress without the
motor system needing to calculate an expected trajectory and comparing this to the actual
trajectory. Instead, a simpler feedback control system of comparing the cursor movement to the
target location could yield the same results, provided that this system does not differentiate
between the ‘actual’ and the ‘strategy’ targets. Such a differentiation requires conscious decision
making: the motor system is known to make online corrections independent of awareness
(Schenk et al. 2005), and patients with visual neglect are still able to adapt to visuomotor
transformations (Rossetti et al. 1998). Also, despite an obvious mismatch between expected and
actual limb trajectories, adaptive recalibration to a prismatic visual shift is absent when
participants can view the entire trajectory of their hand in a reaching task (Redding and Wallace
1996).

In a study by van Asseldonk and colleagues (2009), haptic guidance was provided to
limit the size of motor errors, hindering the recalibration of participants’ movements despite a
gross mismatch between expected and actual trajectories. The correlation observed in the current
study between the magnitude of errors experienced during adaptation and the extent of after-
effects further supports theories of error-driven learning (Thoroughman and Shadmehr 2000). In
the van Asseldonk study (2009), some learning did occur despite the error clamp; these authors
proposed that the adaptation that did proceed was due to movement optimization (Izawa et al.
2008; Shadmehr and Krakauer 2008; Todorov and Jordan 2002), given the cost associated with
pushing against the haptic guidance. However, these effects are also consistent with use-
dependent learning (Diedrichsen et al. 2010). Whether the error detection and correction system
is separate from, or one component of, movement optimization is unknown, and the present
experimental design did not allow us to disentangle these theories.
In addition to reduced errors limiting recalibration in explicitly instructed participants, it may be that explicit processes directly inhibit implicit learning. The implicit and explicit learning systems have been suggested to mutually inhibit each other. Dennis and Cabeza (Dennis and Cabeza 2010) recently reported that participants preferentially recruit the striatum for implicit sequence learning and the hippocampus for explicit semantic categorization learning, with activity levels at these regions being negatively correlated with one another during both implicit and explicit learning. An analogous phenomenon could theoretically contribute to the reduction in sensorimotor recalibration seen here in the explicitly instructed group.

**Catch Trials**

We interpret the catch trial data as reflecting the amount of recalibration that took place, with differences in catch trial performance between the explicit and implicit groups reflecting interference by the explicit strategy. The alternative, that explicit participants were using a counter-strategy to correct for unwanted implicit recalibration, is unlikely. If this were true, we would expect to see an RT difference between explicit and implicit participants on catch trials, but no such difference was observed. We also saw no relationship within explicit participants between RT and DE on catch trials, providing further evidence that explicit participants were following directions and simply not applying the strategy on catch trials.

The timecourse of recalibration followed a similar pattern in implicit and explicit participants. In both cases, recalibration proceeded quickly in the first few blocks of learning. After this initial and rapid progression, recalibration slowed. In either case, recalibration was stable across a large number of trials in explicit participants, indicating that the use of an explicit strategy is a viable method of motor control.
Cognitive Contributions to Adaptation

Substantial evidence exists to support the role of cognitive processes in early adaptation, including impairments in adaptation under dual task conditions (Eversheim and Bock 2001; Galea et al. 2010; Malone and Bastian 2010; Taylor and Thoroughman 2007; 2008), correlations between rate of adaptation and a measure of spatial working memory (Anguera et al. 2010), and neural overlap between brain regions engaged for specific cognitive and motor learning tasks (Anguera et al. 2010; Remy et al. 2010). We have suggested that error information from a given trial is maintained in spatial working memory and utilized when the learner manipulates the sensorimotor map in order to generate a motor command that is appropriate for the new environment (Seidler et al., in press). When adaptation is in response to a rotation of the visual display, this process likely involves the mental rotation component of spatial working memory (Jordan 2001; Logie 2005). This interpretation agrees with Abeele and Bock’s proposal that adaptation progresses in a gradual fashion across the learning period from small angles of transformation through intermediate values until the prescribed angle of rotation is reached (Abeele 2001). Thus, the engagement of these spatial working memory resources late in adaptation is markedly diminished, as compared to early adaptation, when the new mapping has been formed and is in use.

Our prediction in the current study was that providing spatial explicit instructions would prime spatial working memory processes and result in faster adaptation. While explicit spatial instructions decreased direction error during adaptation, it came at the cost of prolonged reaction times, greater trial-to-trial variability, and reduced adaptive recalibration. These phenomena suggest competition for working memory resources.
The use of an explicit spatial strategy did not preclude implicit recalibration in the current study: about half of the 30° rotation was countered by implicit means, as evidenced by catch trials. Some of this effect may be explained by the initial strategy not fully accounting for the rotation. Errors in early adaptation, the probable result of an incomplete strategy, predicted subsequent recalibration. Some may also be due to participants abandoning the strategy in favor of less cognitively demanding implicit processes. This is supported by the positive trend between recalibration and initial RT, indicating difficulty in applying the strategy.

Conversely, the absence of specific explicit awareness of strategy use in implicit learners does not preclude cognitive contributions to learning. While the polling method used in the present study was designed to make a binary distinction between implicit and explicit learning, converging lines of evidence suggest that the underlying reality more likely resembles a continuum. Our results demonstrate that explicit learning is associated with higher reaction times early in learning, high trial-to-trial variance, and reduced procedural learning. In parallel work by Fernandez-Ruiz and colleagues (2011), constraining RT in a visuomotor adaptation task lead to slower learning, lower variance, and more recalibration, a profile consistent with the implicit group in our study. Likewise, in a recent study by Saijo and Gomi (Saijo and Gomi 2010Saijo and Gomi 2010), reducing explicit awareness by imposing a feedback rotation gradually and in small increments led to lower RTs and more adaptive recalibration.

**Conclusions**

We have shown that an explicit strategy can provide rapid performance improvements during sensorimotor adaptation and is a viable method of control. The use of explicit instructions may therefore be particularly beneficial for tasks where rapid and precise mastery of
a visuomotor transformation is ideal. However, an explicit strategy may be detrimental where consistency in performance during learning is critical, such as in the use of modern robotic surgical tools. The reduced after-effects present under explicit learning conditions demonstrate that less long-term recalibration occurred. This may be advantageous when rapidly switching between transformations is necessary.

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Figure captions

Figure 1. Actual instruction clock face used in the experiment by one representative participant. The circles at 12, 3, 6, and 9 o’clock were drawn by the experimenter to highlight target positions. The lines were drawn by the participant to indicate that he / she understood the direction required to move the joystick in order to hit the four different targets. Lines were hand-drawn in pen on a horizontal surface.

Figure 2. Flow chart used for polling implicit participants after experiment completion. Explicit awareness was attributed to participants whose answers followed the path of the bold grey arrows or otherwise indicated the use of a rotation-based strategy.

Figure 3, Panel A: Mean direction error (DE) for explicit and implicit participants for every trial in adaptation. Bands indicate 95% confidence intervals of mean DE on each trial.

Panel B: Mean reaction time (RT) on every trial for explicit and implicit participants across adaptation. Bands indicate 95% confidence intervals of mean RT on each trial. Catch trials are not included; the RT spikes seen in both explicit and implicit groups are on the first trial of each block. Explicit participants had significantly higher reaction times early in adaptation but this effect disappeared later in adaptation.

Panel C: Mean standard deviation (SD) of direction error for each block of adaptation, in both explicit and implicit participants. Explicit participants were significantly more variable early in adaptation, but performance improved across the adaptation period. Bands indicate 95% confidence intervals of the mean SD of each block.
Figure 4, Panel A: Mean direction error (DE) for explicit and implicit participants for every trial in washout. Bands indicate 95% confidence intervals of mean DE on each trial.

Panel B: Mean reaction time (RT) for explicit and implicit participants for every trial in washout. Bands indicate 95% confidence intervals of mean RT on each trial.

Figure 5, Panel A: Direction error (DE) on catch trials for explicit and implicit participants during baseline blocks (Base) and adaptation. Bands indicate 95% confidence intervals of the mean at each trial. Lowercase As and fine lines indicate adaptation trials, while lowercase Cs and bold lines indicate catch trials.

Panel B: Reaction time (RT) on catch trials for explicit and implicit participants during adaptation. Bands indicate 95% confidence intervals of the mean at each trial.

Panel C: Direction error (DE) vs. reaction time (RT) on catch trials for explicit participants during adaptation.

Figure 6. Intercepts of the exponential DE learning curves for washout vs. adaptation in explicit participants.


Did you notice the task get harder at any point?

Yes

Do you know why it became harder?

No

Did you notice the cursor not move where you intended it to?

Yes

Other/No

No

What did you do to correct for it?

Record Response

Other e.g. "pushed left"

"Thank you for participating in this study!"