In the absence of physical practice, observation and imagery do not result in the updating of internal models for aiming

Nicole T. Ong,

Beverley C. Larssen,

Nicola J. Hodges[1]

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1, corresponding author

School of Kinesiology

210-6081 University Blvd

The University of British Columbia

Vancouver, BC

V6T 1Z1

Phone: 604-822-5895

Fax: 604-822-6842

Email: nicola.hodges@ubc.ca

Abstract

The presence of after-effects in adaptation tasks implies that an existing internal model has been updated. Previously we showed that although observers adapted to a visuo-motor perturbation they did not show after-effects. In this experiment we tested 2 further observer groups and an actor group. Observers were now actively engaged in watching (encouraged through imagery and movement estimation), with one group physically practising for 25% of the trials (Mixed). Participants estimated the hand movements that produced various cursor trajectories and/ or their own hand movement from a preceding trial. These trials also allowed us to assess the development of explicit knowledge as a function of the three practice conditions. The pure observation group did not show after-effects, whereas the Actor and Mixed groups did. The pure observation group improved their ability to estimate hand movement of the video model. Although the Actor and Mixed groups improved in actual reaching accuracy, they did not improve in explicit estimation. The Mixed group was more accurate in reaching during adaptation and showed larger after-effects than the Actors. We suggest that observation encourages an explicit mode of learning, enabling performance benefits without corresponding changes to an internal model of the mapping between output and sensory input. However, some physical practice interspersed with observation can change the manner with which learning is achieved, encouraging implicit learning and the updating of an existing internal model.

Keywords: Observational learning, Visuomotor adaptation, Explicit and Implicit knowledge.

It is universally accepted that physical practice aids motor skill acquisition and as people who move, play sports or administer movement-related advice, we are continually trying to find ways of maximizing physical practice in terms of efficiency and effectiveness. One potential way to achieve this would be to substitute physical practice for some other sort of practice, such as observation or imagery, which is potentially less demanding on the practice participant and easier to deliver. In this experiment we study the relative effects of three methods of practice (involving combinations of observation, imagery and physical practice) on learning to move in a novel environment, similar to that which might be experienced during video game playing, or microsurgery, where the relationship between vision and movements change. We evaluate how learning proceeds in terms of the accrual of explicit knowledge and the effectiveness of learning through measurement of unintentional after-effects, assumed to reflect the updating of an internal model of the relationship between sensory consequences and motor commands.

In earlier experiments, ourselves and others showed that observers could directly learn to adapt in novel dynamic and visuomotor environments through observation (Brown et al. 2009; Mattar and Gribble 2005; Ong and Hodges 2010). However, contrary to conclusions from Gribble and colleagues we argued that the process of learning from observation was qualitatively different from that encouraged through physical practice and that learning in the former case was not mediated by implicit, motor-related processes. This conclusion was based on the absence of unintentional, negative after-effects in the normal environment for observers in comparison to actors, despite significant direct advantages from watching. We hypothesized that the lack of after-effects was the result of a failure to update an ‘internal model’ (Wolpert et al. 1995; Wolpert 1997) of the environment in the observers, potentially related to the lack of generation of motor commands and a corresponding efference copy of a planned movement (e.g., Miall and

Wolpert 1996; Redding and Wallace 1993, 2002; Shadmehr and Mussa-Ivaldi 1994). Therefore, in this experiment, we try and elicit these types of processes in observers through manipulations designed to encourage greater simulation of the action via hand (movement) estimation and imagery conditions. Our primary aim was to promote a type of learning or behavioural effect more similar to that seen in actors, merely by changing how observation takes place. Secondary aims were to study how learning develops during practice in terms of accrual of explicit knowledge and to evaluate how a mixed method of practice, involving both observation and physical practice, affects adaptation learning in terms of after-effects and explicit/implicit processes.

Imagery, observation and action simulation

Researchers have postulated that similar neural activities take place during motor imagery, as seen during overt execution of actions (Clark et al. 2003; Fadiga et al. 1999, Holmes & Calmels 2008; Jeannerod 2001, 2006). Similarly, there is evidence pointing to the involvement of the cortical motor system during action observation (e.g., Rizzolatti et al. 1996; Strafella and Paus 2000). These neural activations are presumed to facilitate movement due to an increase in excitability of the corticospinal pathways or facilitate subsequent movement attempts through rehearsal of similar neural areas involved in execution (Jeannerod, 2006).

One way of encouraging more active simulation during observation is to potentially combine observation with imagery. There is behavioural evidence that learning advantages can be gained from combining these two processes (e.g., Ram et al 2007; Zhang et al. 1992). Although the mechanisms for this combined advantage are not entirely clear, advantages have been postulated to be a result of increased cognitive involvement and/or increased cortical excitability. With respect to the latter hypothesis, there is evidence that imagery ability mediates corticospinal activation during action observation. The amplitude of Motor Evoked Potentials, as measured during Transcranial Magnetic Stimulation of a finger-thumb opposition task, were found to be correlated with validated measures of imagery ability (Williams et al 2011).

There have also been suggestions that motor imagery can encourage processes assumed to reflect the updating of internal models, such as the generation of an efference copy of the motor command. In a sequencing task requiring accuracy and speed, Gentili et al (2006) reported positive effects after motor imagery practice on parameters related to movement speed, despite the absence of electromyographic activity in the muscles and a relative lack of improvement in an eye movement practice group. The authors reasoned that motor-related improvements after imagery practice were possible due to covert operations relating to the availability of an efference copy, allowing a comparison between predicted and actual sensory consequences of the movement by the forward model (Flanagan et al 2003; Wolpert and Kawato 1998).

Based on the proposal that motor imagery might be involved in the generation of efference copies, and that imagery ability potentially mediates cortical involvement during action observation, we combined observational practice with imagery in the current experiment. Observers watched and imagined themselves as the agent of the action during target aiming in visually rotated environments.

Implicit learning through observation

In addition to encouraging greater simulation of the action through observation via imagery instructions, we also required participants to engage in covert simulation through estimation of the hand movement required to produce the observed cursory trajectory. This was again expected to encourage feedforward processes associated with the generation of efference copies and corresponding prediction of sensory consequences. Importantly, the addition of estimation of the path of the hand in relation to perturbed visual feedback allowed us to study how explicit knowledge developed during the adaptation process, with and without observation, and further evaluate evidence for implicit learning in observers and actors.

Traditionally, the processes of learning via observation have been thought to be more cognitive or explicit than processes associated with physical exposure (e.g., Bandura 1986; Carroll and Bandura 1990; Hodges and Franks 2002; Howard et al 1992). Bandura (1986) discussed the difficulty of acquiring subtle, more implicit aspects of movement execution through demonstrations (e.g., intricate organization of muscular contraction patterns to generate action forces). According to both Bandura (1986) and Gentile (1998), physical practice is necessary to fine-tune our movements, involving an implicit, non-verbalizable, mode of learning.

Recently, another view of the observational learning process has emerged. In this view, implicit aspects of movement are thought to be achievable through observational practice. Neurophysiology researchers have provided consistent evidence supporting the existence of a mirror neuron system in the brain that is similarly activated when we 'see' and 'do' an action (e.g., Gallese et al 1996; Rizzolatti et al. 1996). This suggests that processes leading to observational learning may be similar to physical learning. In serial reaction time (RT) tasks, evidence for implicit learning through observation has been demonstrated. Bird et al (2005) showed that compared to controls, observers of a training sequence showed elevated RTs switching from the training sequence to a novel one. However, observers showed no evidence of recognition unless sequences were observed in practice without the corresponding hand actions (see also Kelly et al 2003). Subsequently, Heyes and Foster (2002; also Bird and Heyes 2005) showed that observers were aware of the repetition in a short training sequence, in comparison to a longer sequence, but even in this former case observational practice led to effector-specific learning, often taken as evidence that a more implicit, motor-based representation was acquired, (yet see Wang et al 2011).

Implicit observational learning in an adaptation task, similar to the visuomotor adaptation task of the present study, was reported by Mattar and Gribble (2005). Observers who watched a video of an actor adapting to a mechanical force field learned how to adapt to the unseen forces. They were not more accurate than chance, however, in judging whether the force field they experienced was the same as the one they viewed. Moreover, a verbal secondary task did not interfere with adaptation learning, compared to a joystick movement secondary task, further reinforcing the idea that observational learning can be implicit.

Aims and hypotheses

The aims of the present study were threefold. We wished to encourage action simulation during observation, specifically the generation of an efference copy, through imagery and requirements to engage in prediction of the desired hand movements of actors. If after-effects are elicited in a posttest, following this more ‘active’ observational practice, this would indicate updating of an internal model. Second, we wished to study the processes of learning for observers and actors with respect to the explicit accrual of knowledge and awareness about the visuomotor environment. The development of knowledge will be probed through estimations of hand trajectories of the model’s movement, for an observer group and a second group who will both watch and receive a limited amount of physical practice. Estimations from self-generated movements will also be assessed, for this mixed practice group and actors, such that direct comparisons can be made across the two types of estimations (model and self). Over the course of adaptation, we expected the observers and potentially the mixed group to become more accurate in their explicit knowledge (estimations) of the perturbation, if observation is indeed driven by more explicit processes. Third, through comparisons of an observation group to a mixed group, we were able to test the efficacy of this type of practice method, in comparison to single methods, which has received little attention in the learning literature (*cf*., Shea et al 2000). Comparisons of a mixed group, who receives some physical practice, to both observers and actors, allows us to determine how knowledge develops and influences rate and accuracy of adaptation, as well as the presence and size of after-effects. Due to evidence that explicit and implicit learning processes develop in parallel (Willingham & Goedert-Eschmann, 1999), but at different rates in these types of adaptation tasks (Mazzoni and Krakauer 2006; Smith et al 2006), we predicted that the mixed practice group would adapt at a faster rate than the physical practice group, that they would show more explicit knowledge of the size of the rotation due to their observation experience, as well as demonstrating after-effects. If after-effects are not seen following observation, we expected after-effects for the mixed group would be smaller than for the physical practice group due to the fact that the mixed group would have received less than half the amount of physical practice as these actors.

Method

Participants

Twenty nine, naïve, self-reported right hand dominant participants, were pseudo-randomly assigned to three groups; an observer group (OBS; n = 10; M = 21.6, SD = 3.0 yr; 3=f) that engaged in ‘active’ observation involving imagery and estimation of hand trajectory, an actor group (ACT; n = 10; M= 22.5, SD = 4.5 yr; 5=f) that physically practiced and estimated their own hand trajectory, and a mixed group[1] (MIX; n = 9; M= 25.9, SD = 9.8 yr; 7=f) that observed (75%) and physically practiced (25% of trials). The OBS and ACT groups were assigned first to confirm results from a previous study involving slightly modified procedures (Ong and Hodges

2010). Remuneration of $8/hour was paid and informed consent was obtained according to the ethical guidelines of the University.

Task and Apparatus

These were similar to Ong and Hodges (2010). Important changes from previous are detailed. Participants sat in a chair facing a horizontal, semi-silvered mirror, fixed 30 cm above a graphics tablet (Calcomp Drawing Board VI, 200 Hz) that measured 2D displacement[2]. A monitor, positioned 30 cm above the mirror, reflected an image of the stimuli and cursor onto the mirror. The cursor was controlled by a mouse and custom-made pointing device attached to the right index finger. The visual stimuli consisted of a central start square and 5 radially arrayed targets that were presented 10 cm from the start. Targets were separated by 72°, starting at location 0° through 288°.

Participants were required to aim for targets with their right index finger, 'fast and accurately', by moving the mouse on the graphics' tablet through the designated target. Targets changed from a green to red whenever movement times exceeded 250 ms. After each trial (i.e., aiming movement through one target) participants guided the cursor back to the start without time constraints (and cursor vision). Participants aimed to all 5 targets in one cycle of 5 trials, where each of the targets was presented in a pseudorandom manner.

During physical practice, the ACT group physically moved in the rotated environment and practiced aiming to targets for a total of 200 trials. For 150 trials, vision of the participant's hand and cursor were provided. The hand was illuminated through panels of white light-emitting diodes attached to the underside of the semi-silvered mirror. On 50 trials the hand was occluded by turning off the lights (see Table 1 and Procedures).

Participants in the ACT group provided verbal estimates of their own hand trajectory on 25 trials when vision of their hand was occluded (self-estimation). A “star display” of 72 straight lines was digitally presented and viewed on the semi-silvered screen immediately after the trial; each line starting at 1 cm from the origin (i.e., the start square) and extending to a circumference of 10 cm from the origin. The lines were separated by 5° and represented 72 possible hand trajectories. At the termination of each line, a number from “1” to “72” was sequentially assigned in the clockwise direction. The location of the start number “1” was randomly assigned for each star display trial to prevent recall effects. Also shown on the star display was the location of the target in the preceding (cursor-vision only) trial.

During observational practice, the OBS and MIX participants watched a gender-neutral video display of a male trained model’s lower arm and hand movements and his cursor trajectory feedback when aiming in a 30° clockwise (CW) rotated environment. Different from Ong and Hodges (2010), observers were immersed in the environment of the actor, such that they sat in a chair in the mirror-box set-up, and watched the video display of the actor’s movements reflected off the mirror. To create the video, a male volunteer received 200 training trials of the rotation task and was able to accurately guide the cursor to the targets. Following training, we recorded 8 blocks (t=200) of reaching movements in the 30° CW environment (mean constant errors: blk 1 = 2°; blk 2 = 0.6°; blk 3 = 0.5°; blk 4 = 0°; blk 5 = 0.3°; blk 6 = 0.3°; blk 7 = -0.1°; blk 8 = 0.3°). Because observers were required to estimate the trajectory of hand movement from the cursor trajectory we felt this would be facilitated by showing a model aim accurately to one of the 5 targets. On 50 trials, only vision of the “correct” cursor trajectory was shown on the video (i.e., no vision of the model’s hand).

Procedure

Before testing, the revised Movement Imagery Questionnaire (MIQ-R; Hall and Martin 1997) was administered to the OBS and MIX groups. Out of a maximum score of 7 for each item (4 items per imagery component), the averaged scores for the visual and kinesthetic components of the MIQ-R respectively were 5.75 (*SD* = 1.09) and 5.80 (*SD* = 1.01) for the OBS group, and 6.31 (*SD* = 0.85) and 5.64 (*SD* = 1.26) for the MIX group.

The experiment was divided into three consecutive phases; pretest, adaptation, posttests (Table 1). Approximately two minute breaks were given between each phase to allow the participant to rest, to provide instructions and to make changes to the computer program. Participants were first given the opportunity to familiarize to the general task demands in a normal (veridical) environment, where the movement of the cursor corresponded directly to the hand movement. After familiarization, participants were pretested (*t*=50) in a normal environment without visual feedback of cursor or hand (i.e., proprioceptive reaching), providing a baseline comparison for potential after-effects in posttest 1 and posttest 3 (each phase, *t*=50), which were conducted under conditions identical to the pretest. The visuomotor conditions imposed were explicitly explained to the participants before the start of each phase. In the normal environment participants were told that they should aim to the target with their index finger. Under novel visuomotor conditions when the trajectory feedback was rotated, participants were told that the forthcoming environment was different from the normal environment and the response of the cursor to hand movement had changed. They were told that under these conditions the task was to guide the visual cursor to the target.

During adaptation, both ACT and MIX participants physically practised in the 30° CW rotated environment. The objective was to direct the cursor accurately to the target, while moving as fast as possible and in a straight-line (uncorrected) trajectory. To counteract the CW cursor rotation, participants would have to aim their index finger 30° counterclockwise (CCW) to each target (although they were not explicitly told this).

The ACT group received 200 trials (40 cycles/8 blocks of 25 trials) of physical practice in the rotated environment (see Table 1). Of these trials, 150 were performed with feedback of their hand movement and cursor and 50 interspersed trials were performed with only cursor vision. After half of the cursor-vision only trials (t=25), the star display was presented to obtain self-estimation of hand movement. The cursor-vision only trials and self-estimations were randomly distributed throughout practice with the constraint that there was a minimum of 5 cursor-vision only trials in each 25 trial practice block and a minimum of 2 self-estimation trials. These participants verbally indicated the line that best represented their own hand trajectory corresponding to the preceding cursor-vision only trial and responses were recorded. After every 10 cycles (50 target aiming trials), participants were given a short rest.

The OBS group received 200 trials of observational practice. They were informed beforehand that they would be tested in the same environment later. Similar to the ACT group, 50 of the video trials were cursor-vision only trials that occurred in the same interspersed schedule as the cursor-vision only trials for the ACT group and on the same half of these the OBS participants estimated the model's hand movement (model-estimation). Therefore, as with the ACT group, the cursor-vision only trials and subsequent model-estimation were distributed throughout practice with the constraint that 5 trials of every 25 trial block were cursor-vision only and a minimum of 2 of these were model-estimation trials. During the fifth cycle (trial 22), the OBS participants were instructed to begin to imagine that it was their hand they viewed and to try and feel that it was their hand as they watched the video, even though their hand remained stationary. Imagery instructions were delayed to prevent overwhelming the observers with instructions at the start of the experiment. Based on pilot testing, most participants were familiar with the adaptation condition to begin imagery practice by the fifth cycle. Reminders were given at the beginning of the 11th, 21st and 31st cycle to keep engaging in imagery while they were watching the video.

The schedule of practice for the MIX group was chosen to provide the same amount of feedback-based (i.e., hand and cursor trajectory) practice as the observational practice group (t=150), while also allowing for physical practice and matching of total practice amount across the groups (t =200). The MIX group was matched to the ACT group in terms of number of physical practice trials without vision of their hand (t=50), with 25 of these trials requiring self-estimation of hand position. The cursor-vision only physical practice trials were presented in the same schedule as those for the ACT group. The MIX group also received 25 additional observation trials without vision of the hand (i.e., no feedback) in order to obtain estimates of the model's hand position (i.e., model-estimation). These additional trials were inserted into the practice schedule under the constraint that there were at least 2 model-estimation trials per block of 25 trials and that there were no more than 2 consecutive cursor-vision only trials in the overall practice schedule.

After the first posttest in the normal environment to test for immediate after-effects, all participants completed a second posttest in the 30° CW environment (t=50, with cursor feedback) to test for direct learning effects, followed by a final posttest in normal conditions to retest for after-effects.

Data reduction and analyses

Data collection, filtering and derivation of spatial/kinematic information were identical to a previous study (Ong and Hodges 2010). Movement direction was measured as the angle from the origin (middle of the start square) to the position of the cursor at peak tangential velocity. The key dependent variable, directional error from the intended target, was calculated as the difference between movement direction at peak tangential velocity and target location. A positive value or negative value for error denoted a CW or CCW directional error respectively. Estimation error was computed as the directional error between the estimated hand trajectory and the actual hand trajectory.

Movement trials that exceeded 300 ms were excluded from analyses, to discard trials that potentially included online corrections. This resulted in the exclusion of 1.9 % of the total trials executed by all participants (ACT = 3.0 %, OBS = 1.2 %, MIX = 0.7%).

Mean directional constant error (CE) for physical aiming and mean directional CE for estimation trials were computed for each block of trials. Statistical comparisons involved mixed-factor analyses of variance (ANOVA), with Group (ACT, MIX and/or OBS) as between-factors, and Block (8, 5 or 2) and Time (pretest vs. posttest1 or postest1 vs. posttest3) as within-factors.

Adaptation practice

To test for adaptation during initial exposure to the CW environment, the ACT and MIX groups aiming errors (CE) were first compared on cursor-vision only trials (t = 50). These were analyzed across the 8 blocks of practice (min. of 5 trials/block) in order to accurately convey the adaptation process.

For comparison with the estimation data, mean CEs in aiming were also computed for the 25 trials where self-estimations of hand movement were also required. These errors in aiming were calculated across 5 blocks of 5 trials each and compared to the self-estimation directional errors in a 2 Group x 2 Error type (aiming or self-estimation) x 5 Block ANOVA. Errors in model-estimation were also computed as a mean for each 5 trial block and compared for the OBS and MIX groups in a 2 Group x 5 Block ANOVA.

After-effects

We compared the pretest data to posttest1 and postest1 to posttest3 separately to determine whether 1) the observation conditions in the absence of any physical practice resulted in unintentional after-effects and 2) how the addition of physical practice moderated the appearance of after-effects. A block factor was included in this analysis to test for persistency in these effects.

Direct effects of learning

To test for direct benefits of observational practice when first exposed to the CW environment we first compared the 3 groups in postest2 in a 3 Group x 2 Block ANOVA. In a second analysis we compared the first two blocks of adaptation practice for the ACT group to the posttest2 data for the OBS group to determine the relative benefits of prior observational practice (2 Group x 2 Block ANOVA).

Partial eta squared (η^2_p) values are reported as measures of effect size and post hoc analyses were conducted using Tukey HSD (p <. 05). Greenhouse-Geisser corrections were applied for violations to sphericity.

Results

Adaptation practice

Aiming error

The error data for the ACT and MIX groups are shown on the left side of Figure 1 across the 8 practice blocks for cursor-vision only trials. Positive errors show under compensation in aiming. As would be expected, there was a tendency to move the hand closer to the direction of the target, especially during early practice trials. Both groups improved as evidenced by a block effect,

$F(2.55, 43.51) = 13.90$, $p < .001$, $\eta^2_p = .45$. There was also a group effect, $F(1,17) = 7.02$, $p < .05$, $\eta^2_p = .29$. The MIX group ($M = 3.14°$, $SD = 8.29°$) was more accurate than the ACT group ($M = 10.31°$, $SD = 8.69$)[3] although contrary to predictions, this was not dependent on block, $F(2.55, 43.51) = 1.50$, $p = .23$.

Estimation errors

In Figure 2 we have given the directional error means (CEs) in aiming (a) and self-estimation errors (b) across each set of 5 trials ($t = 25$) where self-estimations of errors were required (for the ACT and MIX groups). Both groups estimated their hand to be closer to the cursor than it actually was (i.e., under-estimated the rotation, as indexed by positive errors). Although the group (F = 1.50) and block (F = 1.02) effects were not significant, there was a significant error-type effect, $F(1,17) = 55.17$, $p<.001$, $\eta^2_p = .76$ and a Group x Error-type, $F(1,17) = 14.01$, $p<.001$, $\eta^2_p = .45$, Error-type x Block, $F(2.71, 46) = 11.35$, $p<.001$, $\eta^2_p = .40$ and a 3-way interaction, $F(2.71, 46) = 3.09$, $p<.05$, $\eta^2_p = .45$.

Errors were larger for self-estimations in comparison to actual aiming errors and errors decreased across block for aiming errors only. Although aiming performance improved, knowledge did not. As remarked above, the MIX group was significantly more accurate at aiming than the ACT group, but both groups showed similarly high self-estimation errors. The 3-way interaction was due to the fact that movement errors showed a general decrease across the first few blocks, in comparison to estimation errors which showed a general increase from block 1 to block 2. After the 2^{nd} block of practice, self-estimation errors did not differ between the groups, but the MIX group remained more accurate in actual aiming than the ACT group.

The OBS and MIX groups were also compared on their estimations of the model's hand trajectory as shown in Figure 2b. Again, positive errors indicated an underestimation of the size of the rotation. Only the OBS group improved in their estimations despite a significant block effect, $F(2.6,43.5) = 6.01$, $p < .01$, $\eta^2_p = .26$. This was confirmed by a Group x Block interaction, $F(2.6,43.5) = 5.93$, $p < .01$, $\eta^2_p = .26$. There was no group effect, $F < 1$. Although no statistical comparisons were made due to the different groups involved, errors in self-estimation (M = 16.35°, SD = 7.06°) were generally higher than errors in model-estimation (M = 11.41°, SD = 6.72°).

After-effects

Aiming errors under normal conditions are illustrated on the right side of Figure 1 (posttest1 and posttest3). Negative errors indicate errors in the CCW direction, showing a continued aiming bias to direct the hand in the direction of the learnt CW rotation even though no rotation is required or intended. Comparison of the pretest to posttest1 yielded significant effects of group, $F(2,26) = 20.36$, $p < .001$, $\eta^2_p = .61$ and time, $F(1,26) = 112.31$, $p < .001$, $\eta^2_p = .81$, and the predicted interaction, $F(2,26) = 28.92$, $p < .001$, $\eta^2_p = .69$. Errors increased in the post-test, indicative of after-effects, for the ACT and MIX groups only. These groups showed significantly more error than the OBS group in posttest1, and they were significantly different from each other. Although there was also a Group x Block effect, $F(2,26) = 5.70$, $p < .01$, $\eta^2_p = .31$, the 3-way interaction was not significant, $F(2,26) = 1.68$, $p = .21$.

Tests for after-effects following a second adaptation period (in posttest3 compared to posttest1) yielded a significant time effect, F(1,26) = 54.45, p<.001, $\eta^2_p = .68$, due to an increase in the negative (CCW) bias in aiming. Importantly, this increase in error from posttest1 to posttest 3 (following 50 physical aiming trials) was moderated by Group, F(2,26) = 15.63, $p<.001$, $\eta^2_p = .55$. This was due to the significant increase in error for the OBS group only in posttest3, indicative of after-effects. In posttest3, the MIX group continued to show larger after-effects than the other 2 groups, who did not differ from each other. There were a number of effects involving Block, including a 3-way interaction, $F(2,26) = 4.67$, $p<.001$, $\eta^2_p = .26$. Generally errors decreased across blocks, with the exception of errors for the OBS group in posttest1.

Direct-effects of learning

We first compared errors in posttest2, performed under CW conditions for the 3 groups as a function of block. There were no significant differences across the 3 groups ($F=1.10$), despite the fact that the ACT group had received 100% physical practice, the MIX group had received only 75% physical practice and the OBS group had not received any physical practice (see Figure 1). Errors did not differ across the 2 blocks of testing (50 trials, $F<1$). To illustrate potential benefits associated with observational practice, we compared the OBS groups' errors during their first exposure to the CW environment (i.e., posttest2) to the first 2 blocks of adaptation practice for the ACT group. A significant group effect, $F(1,18) = 27.06$, $p < .001$, $\eta^2_p = .60$, was due to low overall error for the OBS group ($M = -1.22°$, $SD = 6.25$) in comparison to the ACT group ($M = 19.58°$, $SD = 11.97$). Observational practice before physical practice benefited performance. A Group x Block interaction, $F(1,18) = 5.72$, $p<.05$, $\eta^2_p = .24$ was due to a decrease in errors across blocks for the ACT group only.

Discussion

In this experiment there were three aims: 1) to test for after-effects in observers who were additionally encouraged to engage in imagery and to estimate the sensory consequences of observed reaches in rotated environments; 2) to study the development of explicit knowledge about these rotations and; 3) to compare a mixed schedule of observational and physical practice to either condition in isolation, both with respect to aiming accuracy and explicit knowledge.

With respect to these aims, observers failed to show after-effects, but showed a significant accumulation of explicit knowledge about the type of rotation. The mixed practice group was more accurate during adaptation than the actor group and showed some awareness of the size of the rotation that did not improve with practice, contrary to observers. Moreover, this mixed practice group who received only 50 physical practice trials, showed significant and large unintentional after-effects.

Absence of after effects in observers

Replicating previous work (Ong and Hodges 2010), observers did not show after-effects, despite showing they had adapted to the rotated environment on subsequent testing. The addition of imagery and estimation of hand trajectory, designed to encourage (greater) simulation of the movements of the actors and potentially engage feedforward processes, was not sufficient to promote the same type of learning as seen for actors. There was no evidence that an implicit, internal model for reaching had been updated as a result of observation. In two tests we showed that some physical practice was necessary to bring about after-effects, as evidenced by the mixed group in posttest1 and by the observers in posttest3. Similar conclusions about the limits of observational practice in encouraging motor-based representations have been made recently by authors studying sequencing learning (e.g., Boutin et al 2010; Gruetzmatcher et al 2011).

There has been the suggestion that imagery engages motor-related processes similar to those of physical practice, promoting the development of an efference copy of the descending motor commands, which in combination with a forward model, provides a prediction of sensory consequences (Gentili et al 2006). The additional requirement to estimate the hand movements needed to produce the rotated cursor trajectory was designed to promote this process. Despite the addition of these two conditions (imagery and estimation) no after-effects were seen in the observers. This would suggest that either feedforward processes are not responsible for after-effects (*cf*., Bernier et al. 2006), or that these conditions were not sufficient to bring these about. As suggested elsewhere, it is possible that two different forward models are developed through practice with a differential emphasis on self-produced or proprioceptively guided movements and externally produced or visually guided movements (e.g., Miall and Wolpert, 1996; Clower and Boussaoud, 2000; Hwang, Smith & Shadmehr, 2006). In addition to a more implicit model that operates during execution and leads to updating of internal models there is also the potential for an offline, strategically driven forward process that allows for modeling of the external environment. This process is demanding of cognitive resources, can affect motor planning (and learning), but alone, does not lead to updating of internal models.

Explicit processes encouraged through observation

The observers demonstrated significant improvements in estimations of the model's hand movements (i.e., sensory consequences not due to participants' motor output). Even though the mixed group received the same amount of observational practice as the observers (150 trials with vision of the hand and cursor), this mixed group did not improve in their estimations and underestimated the size of the rotation more than the observers in the final block of practice. This would suggest that physical practice moderated the accurate build-up of explicit knowledge in this task. Further, the physical practice groups (ACT and MIX) did not improve in self-estimations of their own movements over the course of practice, even though aiming significantly improved. After the first block of practice, self-estimated errors were always greater than estimations based on the model's performance, again supporting this moderating influence of physical practice on the build-up of accurate explicit knowledge and the intriguing suggestion that observers are better able to detect errors in others than in themselves. These data also support the idea that even relatively small amounts of physical practice (50 trials) results in adaptation via more implicit means. These conclusions are further supported by evidence of unintentional after-effects for the ACT and MIX groups, but not for the OBS group. It is not the build-up of explicit knowledge per se that moderates the appearance of after-effects, but rather the lack of implicit learning processes that appear only to be brought about in this task by physical practice.

Our findings fit well with existing research where explicit knowledge has been directly manipulated during visuomotor adaptation practice. Mazzoni and Krakauer (2006) provided actors beginning to adapt to a visuomotor rotation with an explicit strategy (to aim for a neighbouring clockwise target) that enabled them to perform accurately from the start. However, as practice progressed actors began to make increasingly larger errors in the clockwise direction, meaning that they were overcompensating for the perturbation. The after-effects later demonstrated by the actor group were similar to a control actor group that was not provided with an explicit strategy (see also Wang et al, 2011). These authors argued that implicit learning processes came to dominate explicit knowledge and awareness. The mismatch between forward predictive processes and actual feedback, continued to result in a perceived discrepancy, somewhat regardless of any competing, explicit strategy, causing an implicit update of the internal model for aiming. These results support our suggestion that acquisition of a visuomotor rotation proceeds implicitly through (minimal) physical exposure or practice, somewhat regardless of the use of a strategy to overcome the rotation.

It is important to acknowledge why our conclusions regarding the explicit nature of observational practice might be different from other literature (e.g., Bird and Heyes 2005; Heyes and Foster 2002). We are not necessarily arguing that observational practice must proceed explicitly, but to date we have not found any evidence supporting a more implicit type of learning process for pure observational practice in these types of tasks. A potential reason for the lack of implicit observational learning could be that hand estimation promoted explicit awareness (see Vidoni and Boyd 2007). However, in a previous study where this estimation was not required, similar effects were observed in terms of accurate explicit knowledge about the size and direction of the rotation and a lack of after-effects amongst observers (Ong & Hodges, 2010; see also Larssen et al in review).

Another explanation for the lack of implicit observational learning could be attributed to task characteristics. Some tasks have inherently more complex or less salient underlying structures, characteristics or rules, such as continuous tracking or ambiguous sequence learning, than discrete unimanual aiming movements that were made in the present visuomotor rotation task. With “simpler” tasks where kinematic characteristics are salient and relatively easy to extract, observers could be more prone to this more strategically driven type of explicit learning.

Benefits of combined observation and physical practice

We have presented evidence that a combination of physical and observational practice is more beneficial for acquisition than just physical practice. This is somewhat surprising given that we only provided physical practice on approximately 25 % of the trials. Moreover, the MIX group showed even larger after-effects in the posttests than the actors. These findings add to existing research (e.g., Shea et al 2000) supporting the use of a mixed schedule of practice, rather than pure physical practice, which may increase risks of injury or financial costs of training. The potential effectiveness of mixed practice methods might lie in the parallel encouragement of two learning processes (explicit and implicit) that have differential, yet potentially beneficial effects on skill acquisition. Indeed, Hwang et al (2006) have also presented evidence showing benefits from the combined effects of explicit (aware) and implicit processes during force-adaptation tasks.

The development of these two processes is somewhat supported by the hand-estimation data from this experiment. The mixed practice group showed more awareness of the size of the discrepancy between the model's hand movement and the cursor trajectory than they did when reporting on the discrepancy between their own movements and the cursor (even though these rotations were the same). In addition, contrary to the observers, there was no improvement in this explicit knowledge with practice (despite the same number of observational practice trials with vision of the hand explicitly alerting to the discrepancy). However, it is important to note that the mixed group did not differ from the observers during their first practice attempts. The only behavioural difference between these groups was seen in terms of after-effects. The absence of after-effects suggests that the internal model of the environment had not been updated for observers. Although this might be considered negative and indicative of a less robust mode of learning (e.g., Welch, 1986), in other work we have shown that concurrent observation of two opposing rotational environments actually benefits the recall of both in comparison to concurrent physical practice (Larssen et al in review). Depending on the goals of practice and potentially the time-frame when learning is assessed, observational practice could be considered superior to methods involving physical practice.

Returning to the framework of internal models to explain these data, it appears that action experience before observation or combined with observation might allow updating of implicit, internal models in a manner similar to physical practice (something we are currently testing in our laboratory). If this is the case, then there would seem to be evidence that feedforward, predictive processes can be activated through covert simulation (i.e., imagery and observation) and based on observation of someone else's feedback, learning can occur, or continue to occur implicitly. This would explain the large after-effects seen for the mixed group, in comparison to the absence of these after-effects in the observe-only group and to the comparatively smaller after-effects seen in the physical practice group, both who had 25 fewer trials of total practice (observation and physical practice) than the mixed practice group.

In summary, we have shown that observers can learn to adapt to novel visuomotor environments through observational practice. However, this process of adaptation is different from what is seen amongst physical practice participants. This is evidenced behaviourally by a lack of after-effects when observers are knowingly transferred to a normal environment following observation, despite significant after-effects seen in actors. Moreover, we have shown that these after-effects can be brought about by few physical practice trials (either interspersed in practice or after a period of observational practice). It appears that observational practice, at least for this task, does not promote learning via implicit/motor driven means, in contrast to physical practice and a combined method of practice. Although awareness of errors per se does not prevent true adaptation and the updating of an internal model, it appears that the absence of physical practice (either efferent-related processes or the absence of self-generated feedback, reafference), prevents this type of learning from taking place.

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Footnotes

1: One participant was excluded at the analyses stage due to unusually large pretest aiming error.

2: A Calcomp Drawing Board III (225 Hz, 200 lines/cm resolution) was used for data collection for the OBS and ACT groups. Due to a malfunction after testing these groups, a new version of the tablet was used for the MIX group. The main difference between these tablets was that a custom made pointing device was used with the first tablet, allowing for movements of the index finger on the tablet (with the mouse attached to the top of the hand). However, this custom made device was not compatible with the new tablet such that a new mouse was constructed that had a plastic extension with cross-hairs for placement of the index finger. Both devices were calibrated before testing and pilot testing ensured that pre-test errors (i.e., normal aiming) were not significantly different across the 3 groups.

3: To determine whether the requirement to estimate their own hand trajectory impacted errors for the ACT group, we compared this group's performance to a previous group who practiced with vision of the hand and cursor in a previous experiment (Ong and Hodges 2010). A 2 Group x 8 Block ANOVA yielded no significant group-related effects, both Fs < 1.

Table 1: Number of trials (t) for each experimental phase and associated practice type (act or observe) and vision condition (with or without vision of the hand, cursor trajectory was shown in adaptation and posttest2) as a function of group (actors, ACT, observers, OBS and mixed practice, MIX).

Group/Phase:	Pretest (normal)	Adaptation (30°)				Posttest1 & 3 (normal)	Posttest2 (30°)
		Act		Observe		Act	Act
Vision:	No Hand	Hand	No Hand	Hand	No Hand	No Hand	No Hand
ACT							
Practice, t =	50	150	50	0	0	50	50
**(Estimate, t =)*			*25(self)*				
MIX							
Practice, t =	50	0	50	150	25	50	50
**(Estimate, t =)*			*25(self)*		*25(model)*		
OBS							
Practice, t =	50	0	0	150	50	50	50
**(Estimate, t =)*					*25(model)*		

* The number of estimate trials (in italics) are included in the overall practice count.

Figure Captions

Figure 1: Mean directional constant error (degrees) for the ACT (squares), MIX (triangles) and OBS groups (circles) during the ‘normal’ pretest (2 blocks of 25 trials each), across the 8 blocks of adaptation practice to the 30° CW rotation on cursor-vision only trials (*t* = 50, min 5 trials/block), and during the 3 posttests (posttest 1 = normal vision test for after-effects, posttest 2 = 30° CW rotation and posttest 3 = normal vision, final test for after-effects). Positive error value = error in the clockwise direction to the target. Error bars = *SD*.

Figure 2a & b: a) Mean directional constant error (degrees) in aiming movements during adaptation on the self-estimation, cursor-vision only trials (5 trials/block), for the ACT (triangles) and MIX (circles) groups. In b) errors in estimation (degrees) of hand trajectory compared to actual hand position in a preceding cursor-vision only trial (5 trials/block). Self-estimation errors (closed symbols & dashed lines) are shown for the ACT and MIX groups. Model-estimation errors (open symbols, dashed lines) are shown for the MIX and OBS (squares) groups. Positive error value = error in the clockwise direction to the target. Error bars = *SD*.

Fig 1

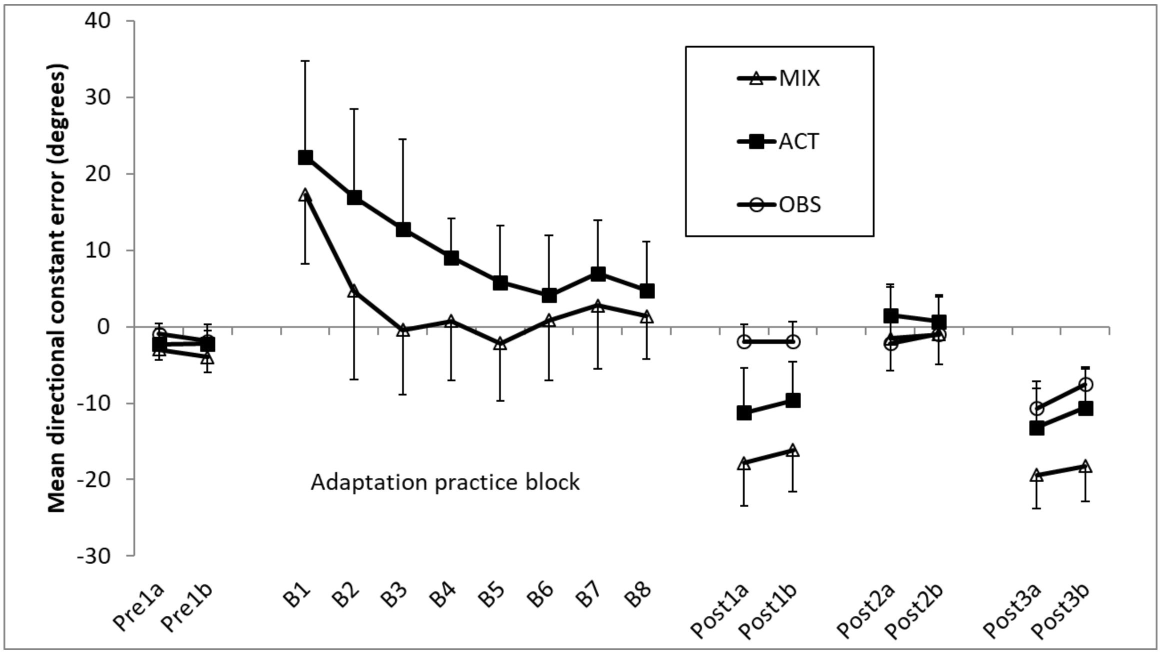


Fig 2

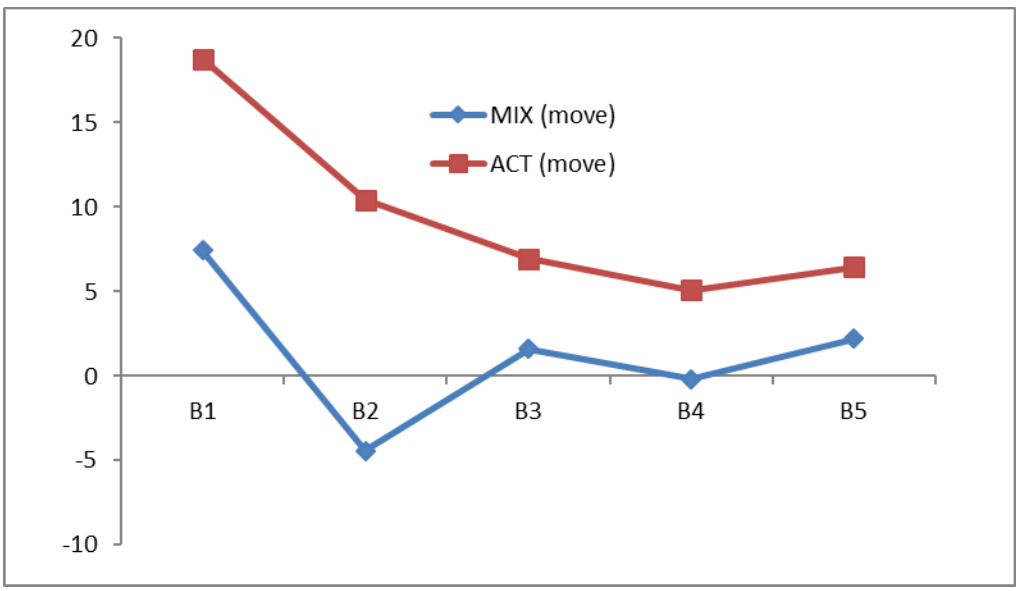
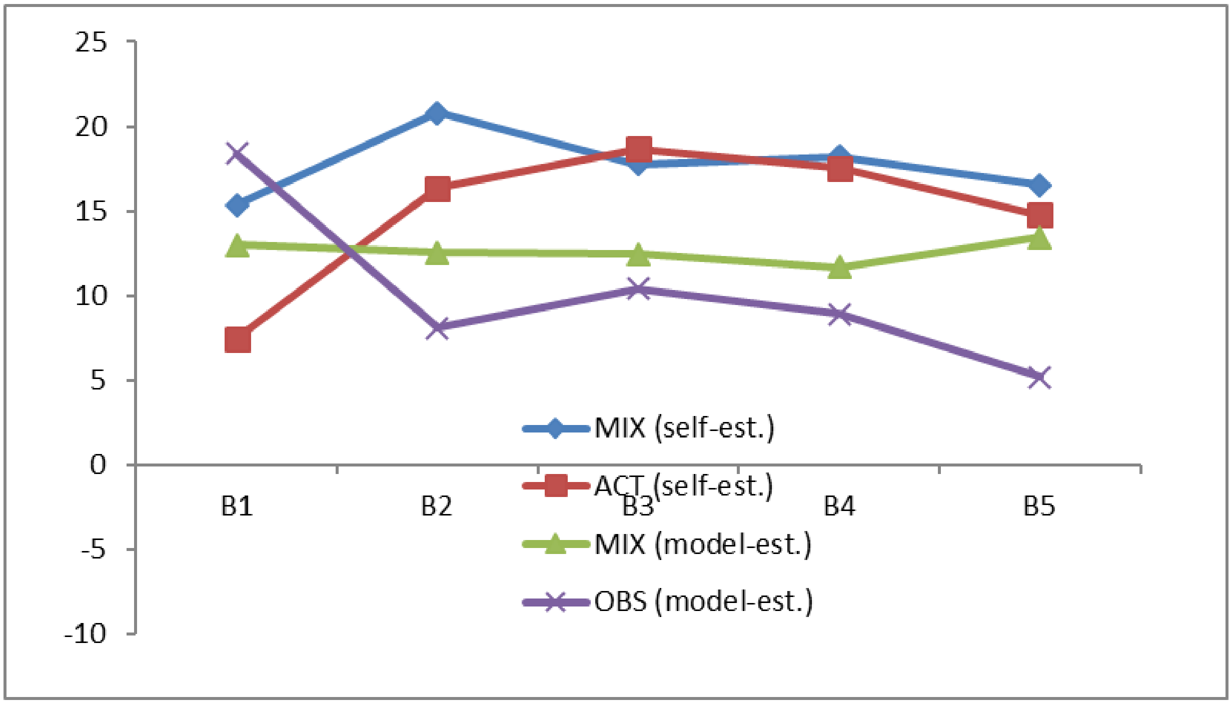


Fig 3



25
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B1
B2
B3
B4
B5
MIX (self-est.)
ACT (self-est.)
MIX (model-est.)
OBS (model-est.)