Reporting affects explicit knowledge in visuomotor rotation in ways not measured by reporting

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Abstract

Visuomotor rotations are frequently used to study cognitive processes underlying motor adaptation. Explicit aiming strategies and implicit recalibration are two of these processes. A large body of literature indicates that these two processes are dissociable and perhaps even independent components. Various direct and indirect methods have been used to dissociate the two processes. Discrepancies have been found between these different methods. They may arise for different reasons, but one reason may be that the different measures reflect different components of explicit and implicit knowledge. They may also be because of effects of the measurements themselves on the amount of explicit and implicit learning. The goal of this study was to directly compare verbal reporting, a direct measure of explicit knowledge, with indirect measures. We thus compared three different measures in two different conditions: during consistent reporting and during intermittent reporting. Our results show that our two conditions lead to a dissociation between the measures. In the consistent reporting group, all measures showed similar results. However, in the intermittent reporting condition, verbal reporting showed less explicit and more implicit knowledge than our two indirect methods. Verbal reporting seems to be insensitive to the changes in explicit knowledge caused by reporting. These findings suggest that verbal reporting reflects different components of explicit knowledge than those reflected in our indirect measures. A more sophisticated approach, including multiple components of explicit knowledge, may be necessary in order to fully understand motor adaptation.

Introduction

Classically, adaptation to visuomotor rotations is assumed to consist of at least two main underlying processes: an implicit process – which is slow, temporally stable, expressible at low reaction times and rigid in different conditions – and an explicit process – which learns rapidly, requires a long preparation time and is highly flexible (Taylor and Ivry 2011, Taylor, Krakauer et al. 2014, Bond and Taylor 2015, Haith, Huberdeau et al. 2015, Huberdeau, Krakauer et al. 2015, McDougle, Bond et al. 2015). A myriad of methods are used in visuomotor rotation tasks to assess these processes (Fernandez-Ruiz, Wong et al. 2011, Heuer and Hegele 2010, Taylor, Krakauer et al. 2014, Haith, Huberdeau et al. 2015, Werner, van Aken et al. 2015, Morehead, Taylor et al. 2017). Some methods are considered direct: these include asking subjects where they are aiming (Taylor, Krakauer et al. 2014) and questionnaires at the end of the experiment (Hwang, Smith et al. 2006, Benson, Anguera et al. 2011). Other methods are considered indirect: these include manipulating subjects' behavior using different task designs (Haith, Huberdeau et al. 2015, Morehead, Taylor et al. 2017). Since many methods and measures exist, it is of concern to determine whether they are measuring the same thing and to what degree the different measures agree in different conditions.

In order to successfully compare these different methods, we first need to understand some theoretical considerations related to the methods. Verbal reports, for example, are considered the most direct method to assess subjects' explicit knowledge of a task (Timmermans and Cleeremans 2015). Although it may seem very appealing to simply ask subjects about their knowledge, they may refrain or simply be unable to report on certain experiences. Verbal reports may also be contaminated by the observer paradox, which refers to the fact that asking subjects to produce subjective reports or to reflect on their own performance may obscure the very processes that are being monitored (Newell and Shanks 2014, Timmermans and Cleeremans 2015). Indirect methods, on the other hand, assess subject awareness without making explicit reference to the relevant discriminations. These kinds of methods presuppose that awareness of some information and behavioral sensitivity to that same information involve the very same process. However, performance may depend on other factors such as learning of entire stimulus configurations or the learning of micro-rules (Newell and Shanks 2014). Thus, rather than being connected to one of the processes, performance in these tasks is likely to reflect both conscious and unconscious contributions (Jacoby 1991, Cleeremans, Destrebecqz et al. 1998, Timmermans and Cleeremans 2015).

These theoretical considerations shed light on existing literature comparing methods of measuring explicit and implicit knowledge in visuomotor rotation tasks. Bond and colleagues compared an implicit measure derived from self-reported aiming directions with the error that persists when subjects are informed that rotation has been removed at the end of adaptation (Bond and Taylor 2015), called the aftereffect (Taylor, Krakauer et al. 2014, Taylor and Ivry 2013, Hegele and Heuer 2010). Leow et al. (Leow, Gunn et al. 2017) compared Taylor's implicit report measure with implicit adaptation invoked by restricted preparation time and the aftereffect. Both studies report a discrepancy between the implicit learning as derived from reporting and as measured by the aftereffect, although to differing degrees. Interestingly, the reporting group in Leow et al.'s study showed less overall implicit knowledge as measured by the aftereffect compared to the non-reporting group. These differences in estimates could be attributed to time-dependent loss of implicit knowledge (Taylor, Krakauer et al. 2014), to systematical under-reporting of the aiming angle, which would result in an overestimation of implicit learning in the aftereffect or to a reduction of implicit knowledge due to a larger amount of explicit knowledge (Leow, Gunn et al. 2017). However, taking into account the theoretical considerations we described above, we hypothesize that part of the discrepancies arises from comparing methods that do not measure 'pure' explicit or implicit knowledge or methods that capture different kinds of processes.

The contamination of the direct and indirect approaches makes interpretation difficult, especially when comparing results across measures. Differences in the measures may arise because of contamination or because different measures really test different underlying processes. We will manipulate the amount of direct measurement in order to be able to see how much the measurement itself affects behavior. In order to address the tendency of indirect measures to confound implicit knowledge in their measure of explicit knowledge, we will use a method validated in the cognitive science literature for this specific problem. The process dissociation procedure, which we will describe in detail in the methods section, assumes explicit knowledge to be controllable and combines direct manipulation with indirect measurement to isolate implicit and explicit knowledge more effectively (Jacoby 1991, Cleeremans, Destrebecqz et al. 1998, Destrebecqz and Cleeremans 2001, Gaillard, Cleeremans et al. 2014, Werner, van Aken et al. 2015). Discrepancies between the different estimates will give us an indication whether we are measuring the same processes.

In the current study, we thus sought to compare different measures under different conditions in order to assess whether these methods actually capture the same processes. We found direct reporting increases explicit adaptation in a way that reporting itself does not capture. We suggest that these differences indicate the presence of multiple components of both implicit and explicit learning and that more sophisticated methodologies need to be developed in order to fully characterize them.

Materials and methods

Participants

Fifty-three right-handed participants (28 female, aged 24-36) completed the study. Subjects had no prior experience in visuomotor rotation research. The experimental protocol was approved by the Human Subjects Research committee of the Ben Gurion University, and followed the ethical guidelines of the university.

Experimental apparatus and general procedures

We first start with a general description of the experimental set-up, the procedures, and the task. In the following paragraphs we describe the experimental design of the behavioral task in more detail.

Participants made center-out, horizontal reaching movements while holding on to the handle of a robotic manipulandum (Figure 1A). Movement trajectories were sampled at 200 Hz. The stimuli were projected onto a horizontal plane in front of the participants (BenQ MS527, 3300 ANSI lumens). At the beginning of each trial, the manipulandum guided the participants' hand towards a white circle in the center of the display (5 mm radius), which was positioned approximately 45 cm away from the eyes of the subject. After 50 ms, subjects were presented with a small target (red, 7 mm radius) at a distance of 10 cm from the origin. Targets could appear on a circle in one of 8 possible, equally spaced locations (45° between targets). Subjects were instructed to make fast and accurate shooting movements to pass the cursor (3 mm radius, online feedback) through the designated target. After leaving the starting position, participants had between 400 and 600ms to reach the target in order for the target to turn green. The target turned blue and yellow when movements were too slow or too fast, respectively. Additionally, a happy bling indicated target hit and an annoying buzz sound indicated target miss.

The procedures for all subjects included a short familiarization session that was followed by a baseline block. After the baseline block, subjects were exposed to an adaptation period. At the end of adaptation, subjects in all groups performed a posttest, comprised of the full process dissociation

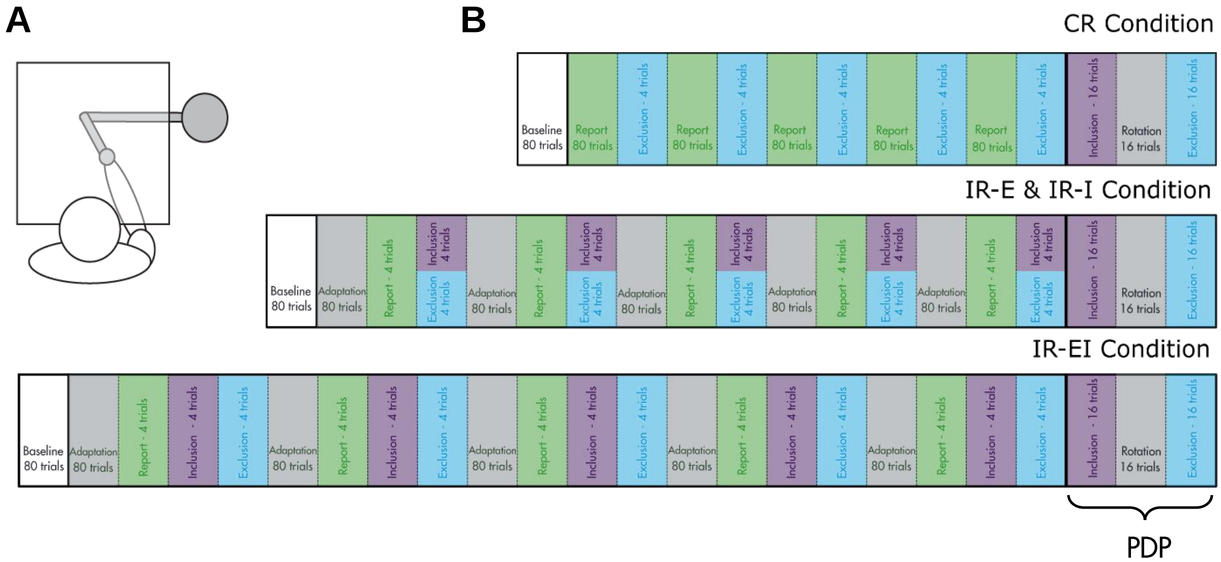


Figure 1 Experimental task. **A)** Subject were seated in front of a desk, which occluded sight of their arm and hand. With their right hand, subjects held the handle of a robotic manipulandum. The visual scene was projected onto the desk in front of the subjects. **B)** Procedures for the four experimental groups: Subjects in the CR group reported consistently throughout the entire adaptation (green boxes) while subjects in the IE, II and the IEI groups performed regular adaptation blocks without reporting (gray boxes). At the end of each adaptation block, subjects performed four exclusion trials in the CR group (light blue boxes), report and exclusion trials in the IE group (green and light blue boxes), report and inclusion trials in the II group (green and purple boxes) or report, exclusion and inclusion trials in the IEI group (green, light blue and purple boxes). Each group started with a baseline block and ended with a Process dissociation procedure block.

procedure. A detailed description of the posttest will be provided in the next paragraph (see also Introduction and Figure 2B). After completion of the experiment, subjects filled out an online questionnaire about the experiment and the task. In the first part subjects had to answer open questions about the nature of the perturbation, and in the second part, the same questions were posed as multiple choice questions.

In order to aid the reader's understanding, we will first describe the different sort of trials used in the experiments. The relationship of the cursor to the hand movement could be one of three different relationships: veridical, no vision, or rotated. Veridical feedback was provided in most baseline trials. In some trials, the visual field was rotated so that the cursor was not precisely on the hand. This included a block of trials during the baseline designed to teach subjects how to report their aiming direction. In these trials, the visual field was rotated on each trial by a different amount governed by a sum of sinusoid. Rotations were between -30° and 30°. This gave subjects practice in reporting changing aiming direction without exposing them to strong adaptation. In the adaptation blocks, subjects were exposed to a consistent 60° rotation of the visual field. Some subjects (the CR group) reported on every trial during the adaptation blocks and others reported only intermittently. Also, during the refresh block between exclusion and inclusion, the cursor was rotated by 60°. Finally, during exclusion and inclusion trials and a small number of baseline trials, the cursor did not appear at all.

Behavioral task

The main goal of this experiment was to compare different measures of the explicit and implicit processes: using reporting developed by Taylor, (Taylor, Krakauer et al. 2014), exclusion (widely used and occasionally called the aftereffect), and the process dissociation procedure adapted to motor learning by Werner (Werner, van Aken et al. 2015). To this end, we designed a visuomotor rotation task in which subjects reported throughout adaptation. We added intermittent exclusion trials, which enabled us to 1) compare the report measure with exclusion measure and 2) assess the time course of both report and exclusion. Since one of our assumptions was that reporting may affect both adaptation and our measures, we compared the consistent reporting group (CR, n = 12) with an intermittent reporting group (IR-E, n = 17). Furthermore, two additional intermittent groups were added in order to control for possible effects of the intermittent measures on adaptation or the measures themselves (Jacoby 1991, Cleeremans, Destrebecqz et al. 1998, Timmermans and Cleeremans 2015): an intermittent reporting inclusion group (IR-I, n = 11) and an intermittent reporting group with the full process dissociation procedure (IR-EI, n = 12). Participants were randomly assigned to one of the four groups. The trial design in all groups was similar (Figure 1B). Prior to the start of the experiment, participants were told that something in the task will change after the baseline block, which may increase task difficulty. They were instructed to continue in trying to hit the target with the cursor. All groups started with a familiarization session of 16 trials, during which subjects could ask questions and become familiar with the apparatus and task. After this, all subjects conducted a baseline block of 80 trials. During the baseline block, 34 trials with veridical feedback were interspersed with 6 trials without visual feedback. In addition, subjects conducted 40 trials of training in reporting their aiming directions. This training consisted of trials with numbered landmarks (Figure 2A) and a random perturbation (see previous paragraph). Landmarks rotated with the target, such that the same landmarks would always appear in the same location relative to the target (Bond and Taylor 2015). Verbal reports were recorded both online by the experimenter and digitally for later verification. After baseline, subjects in all groups performed five adaptation blocks of 80 trials each. The CR group continued reporting throughout the entire adaptation, whereas the intermittent reporting groups reported only for four trials at the end of each adaptation block. Additionally, the CR group and the IR-E group completed four exclusion trials and the IR-I group completed four inclusion trials

(Werner, van Aken et al. 2015) at the end of each adaptation block. The IR-EI group performed both exclusion and inclusion trials (Figure 1B).

Posttest - Process dissociation procedure

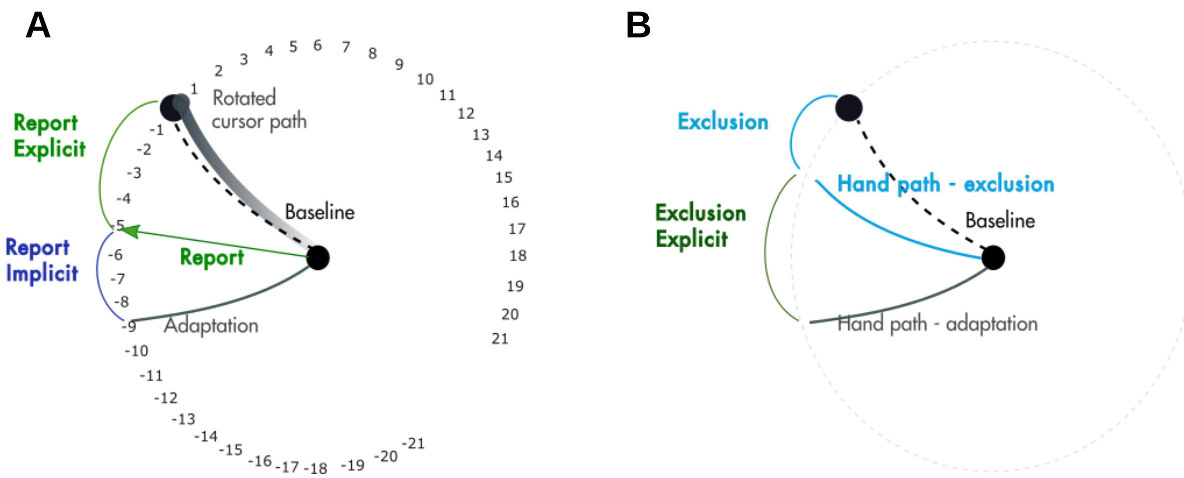
The Process dissociation procedure consisted of 48 trials, 16 of which were exclusion trials, 16 were 'refresh' adaptation trials, and the last 16 were inclusion trials. This procedure assumes that the contribution of explicit and implicit processes to behavior can be estimated from the comparison of two situations. In the first (the inclusion task), explicit and implicit processes both contribute to performance (the inclusion task) or are set in opposition (the exclusion task). In other words, in the inclusion task, both types of knowledge can lead to a correct response whereas in the exclusion task, only conscious knowledge can lead to the correct rejection of a certain stimuli. The inclusion and exclusion task thus only differ in terms of their instructions (Jacoby 1991, Destrebecqz and Cleeremans 2001, Gaillard, Cleeremans et al. 2014, Timmermans and Cleeremans 2015). Before inclusion subjects were instructed to 'use what was learned during adaptation', and before exclusion subjects were asked to 'refrain from what was learned, and perform the movement as during baseline'. Note that the exclusion task closely resembles the aftereffect, however, no cues were provided (Hegele and Heuer 2010) and instructions did not refer to the rotation or to 'aiming right at the target' as is generally the case for instructions of the aftereffect (Taylor, Krakauer et al. 2014). The order of exclusion and inclusion was counterbalanced between participants as suggested by Werner et al (Werner, van Aken et al. 2015).

Movement analysis

To assess task performance, we focused on the directional error (DE), which we calculated as the difference between the target angle and the average heading angle, which was computed as the angle 8 cm along the trajectory. All trajectories were rotated to a common axis with the target location at 0°. Reaction time was defined as the time elapsed between the appearance of the target and the point at which the hand was moving 5 cm/s. A trial was omitted if reaction times exceeded 1000ms or if the subject's movement did not reach the target; 1.5% of all trials were thus excluded. To visualize directional errors, we used bins of four trials each.

From the movement direction of each subject during the different epochs, we obtained different measures:

- The reported aiming direction (five times 80 reports for the CR group and five times four reports for IR-E, IR-I and IR-EI groups)
- The implicit report (calculated from the reported aiming as illustrated in Figure 2A and identical to that used by Taylor et al. 2014; same amount of trials as the reported aiming direction).
- The exclusion (five times four trials for the CR, IR-E and IR-EI groups)
- The exclusion explicit (calculated from exclusion as illustrated in Figure 2A). For computation of the exclusion explicit, we selected the last adaptation bin (4 trials) and from this, subtracted the exclusion bin. This rendered an indirect measure of the explicit aim during the exclusion trials.
- The inclusion (five times four trials for the IR-I and the IR-EI group)
- Awareness index (AI, calculation based on Werner et al., intermittent and final, see following paragraph for a detailed description of the calculations)
- Unawareness index (UAI, calculation based on Werner et al., intermittent and final, see following paragraph for a detailed description of the calculations)



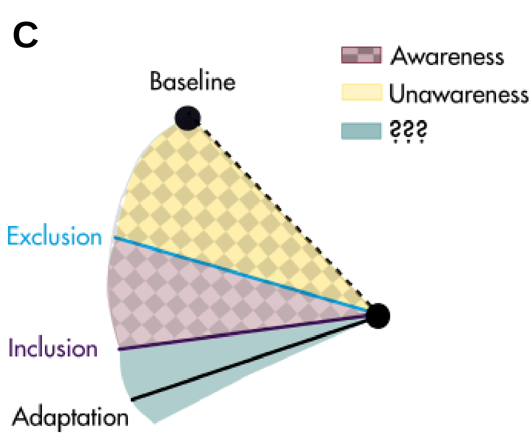


Figure 2 **A)** The difference between reported aiming directions and the hand path during adaptation provides us with the Implicit report measure (Taylor, Krakauer et al. 2014). **B)** The exclusion measure gives an indication of the implicit knowledge a subject has and thus cannot control. By subtracting the exclusion from the hand path during the (last four) adaptation trials, we obtain a measure of the explicit knowledge a subject had and can possibly control. **C)** Process dissociation procedure measure as adapted from Werner et al(Werner, van Aken et al. 2015). The AI (red) is derived from the difference between inclusion and exclusion whereas the UAI (yellow) is equal to the exclusion. AI and UAI do not usually add up to the adaptation (performance), thus there is a part forming possible other processes (teal).

The implicit report measure gives us an indication of the adaptation to which a subject has no explicit verbal access. In contrast, the exclusion measures adaptation over which the subject has no ability to explicitly control That is, when we explicitly ask a subject to aim at the target, the difference between the target and where they actually aim is leftover implicit knowledge not accessible to control. The exclusion explicit, the change in their aiming direction caused by this attempt to aim at the target, thus measures the subjects explicit control over their own behavior. When subjects are asked in the inclusion to return to what they learned, we get a new measure of their ability to control their behavior. This is considered a cleaner measure (Werner, van Aken et al. 2015, Jacoby 1991) and using just the exclusion will thus overestimate subjects explicit control.

Awareness and unawareness indices (AI and UAI)

We calculated an exclusion (EInd) and an inclusion index (IInd) for each subject from the movement directions of the posttest, which was performed at the end of each group. In addition, we calculated these values after each rotation block for the IR-EI group. Exclusion and inclusion indices were determined as follows:

$$EInd = \frac{DE_{\text{Exlusion trials}} - DE_{Baseline\ no\ vFB\ trials}}{DE_{last\ adaptation\ trials} - DE_{Baseline\ trials}}$$

$$IInd = \frac{DE_{\text{Inclusion trials}} - DE_{Baseline\ no\ vFB\ trials}}{DE_{last\ adaptation\ trials} - DE_{Baseline\ trials}}$$

We used 16 consecutive trials for exclusion ($DE_{\text{exclusion trials}}$) and inclusion ($DE_{\text{inclusion trials}}$), and the last adaptation trials ($DE_{\text{last adaptation trials}}$). Mean values of all trials with visual feedback were used for the baseline values ($DE_{\text{Baseline trials}}$) and mean values of all trials without visual feedback were used for baseline without visual feedback ($DE_{\text{Baseline no vFB trials}}$).

The Awareness Index (AI) was calculated as the difference between the EInd and the IInd, and the Unawareness Index (UAI) was derived from the difference between EInd and the mean baseline values:

$$AI = IInd - EInd$$

$$UAI = EInd$$

In order to assess whether subject's awareness or unawareness can be related to the amount of explicit knowledge, we additionally normalized the values of our other explicit measures (the explicit report and the explicit dissociation). This allowed us to calculate compare the different measures on the same scale.

Normalization of measures

In order to be able to compare between the amounts of knowledge measures by the different methods, we normalized all explicit and implicit measures in the same way as the exclusion and inclusion indices. We thus used the directional error of the measures, subtracted trials from baseline trials without visual feedback and then divided this number by the difference between the DE of the final adaptation trials and the DE of regular baseline trials.

Statistical analyses

For statistical analyses, we focused on the difference between 1) adaptation rates between groups, 2) the intermittent measures and their relation to each other between groups and 3) the final measures (final exclusion and inclusion and AI) between groups. Finally, we performed a pair-wise correlation analysis between intermittent and final measures. Unless otherwise noted, we report the mean and 95% confidence intervals for all reported and depicted values. Results in brackets always represent the 95% confidence interval. We forego reporting statistical significance as per the recommendations from Amrhein 2019 (Amrhein, Greenland et al. 2019). Full statistical calculations and hypothesis testing are provided in the supplementary material. Statistical calculations were performed using customized scripts in MATLAB 2018b (The Mathworks, Natick, MA) and SPSS 20 (ANOVAs) (IBM, Armonk, NY) which are available online.

Results

Adaptation and learning rates

The time course of heading angles showed a stereotypical learning curve for all four groups (Figure 3A). However, the learning curves differed between the CR and the intermittent groups: adaptation proceeds slower and reaches asymptote later in the intermittent groups than in the CR group (see difference between blue learning curve and the rest). We compared differences in heading angles early and late in adaptation by computing the average over 1) the last eight trials of the first adaptation block and 2) the last eight trials of the last adaptation block (asymptote of learning). Figure 3B depicts the mean heading angles for early and late adaptation: the CR group showed greater change in heading angles during early adaptation (53.0° [49 - 57]) as compared to the IR-E (45.4° [41 - 49), IR-I (41.5° [37 – 46]) and IR-EI group (43.2° [37 – 49]). These differences of 8°-10° are consistent across groups and are of meaningful magnitude. This difference in heading angles between groups persisted until the end of adaptation although with markedly reduced magnitude (CR: 59.5° [56 – 63]; IR-E: 54.5° [53 – 56]; IR-I: 53.9° [52 – 56]; IR-EI 57.7° [56 – 62]).

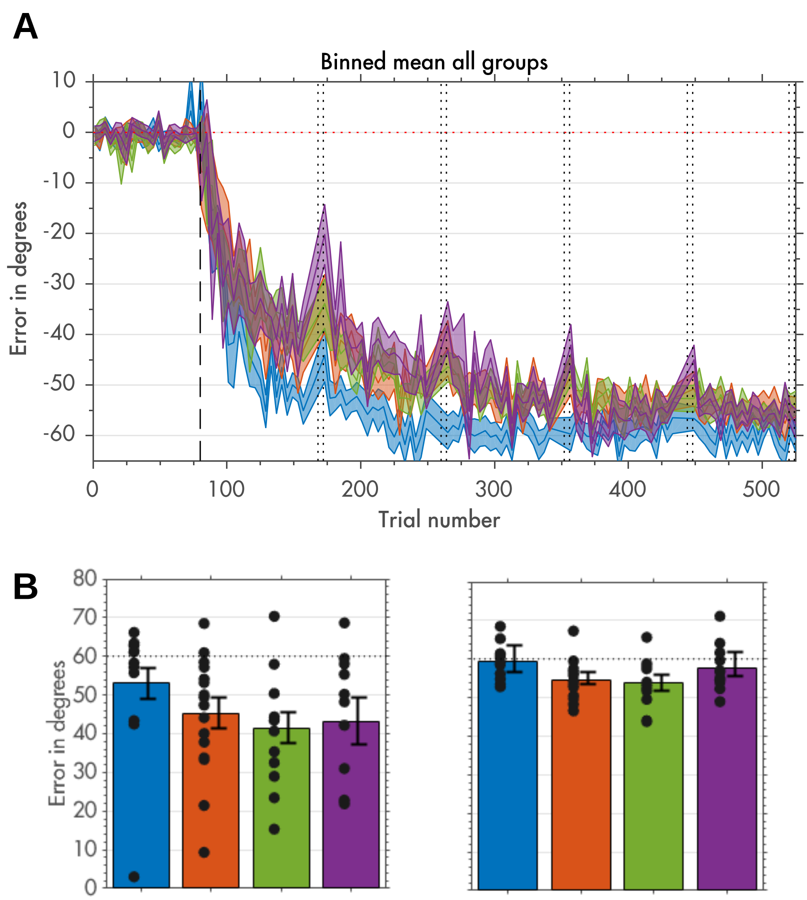


Figure 3 **A)** Binned mean directional error per group. Dashed line shows the end of baseline, dotted lines throughout adaptation show location of test blocks. The posttest (Process dissociation procedure) is not shown. **B)** Early and late heading angles. For the early heading angles, we used the last two bins of the first adaptation block (8 trials) and for the late heading angles we used the last two bins of the last adaptation block (8 trials). In blue is shown the consistent reporting group (CR), in orange the intermittent exclusion group (IR-E), in green the intermittent inclusion (IR-I) and in purple the intermittent exclusion and inclusion group (IR-IE). Black dots denote individual subjects. Error bars show 95% CI.

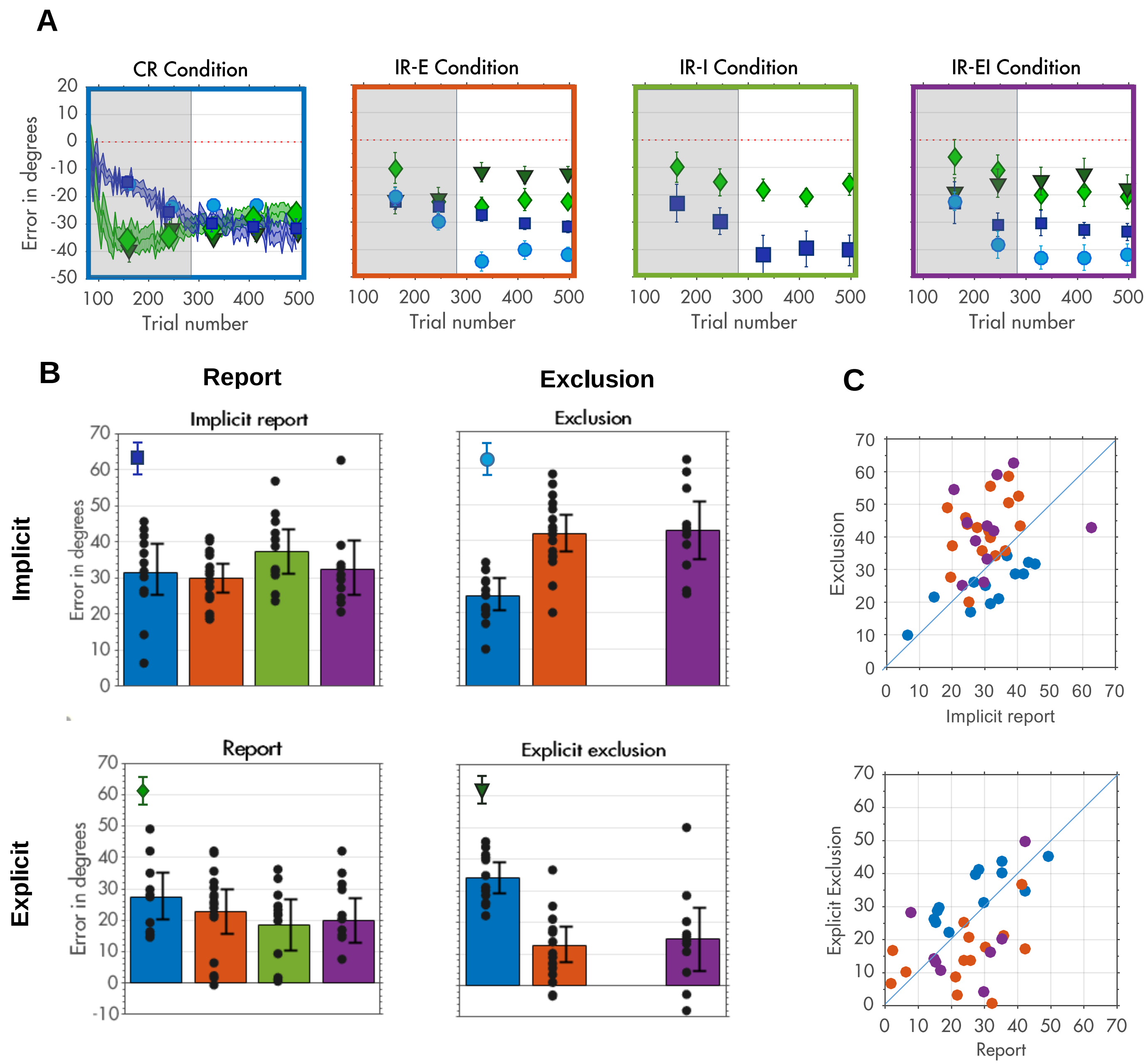


Figure 4 Intermittent explicit and implicit measures across groups. **A**) Time course of measures per group. Each figure depicts intermittent measures for one group (see color codes). Note that subjects in the CR group performed consistent reporting, thus report (light green) and report implicit (dark blue) are shown as a continuous measure. Additionally, a light green diamond (report) and a dark blue square show the test block from which the measures in (B) are derived. Axes border colors correspond to the different groups in (B). **B)** Intermittent measures for each group. Bars show mean of the last three test blocks in (unshaded area in A). Top row shows implicit measures; bottom row shows explicit measures. Left column shows exclusion measures and right column shows report measures. Black dots depict individual subjects; error bars show 95% CI. **C)** Explicit and implicit measures plotted against each other. The upper figure shows exclusion vs implicit report whereas the bottom figure shows explicit exclusion vs report.

Intermittent measures

Different measures were used in order to assess the level of explicit and implicit knowledge throughout and at the end of adaptation. Explicit learning was estimated by the reported aiming directions, the exclusion explicit (derived from exclusion trials) and the AI (awareness index), derived from the process dissociation procedure measured after the adaptation phase. Implicit learning was estimated by means of the report implicit (derived from the reported aiming angles), the exclusion measure and the UAI (unawareness index), calculated again from process dissociation procedure. In the following paragraph, we will first describe the intermittent measures and their relation to each other within and between groups. After this, we will describe the final measures (AI and UAI).

Figure 4A depicts the time course of the intermittent measures for all groups. All measures stabilized in the last three test blocks (white area in Figure 4A), we thus used the average value of these blocks for any comparisons between measures and groups. Both intermittent implicit measures (exclusion and implicit report) rise slowly and monotonically in all groups (Figure 4A, light blue circles and dark blue squares). Implicit report showed similar levels of implicit learning between CR, IR-E and IR-EI groups (Figure 4B, top right column; CR: 31.4° [25 – 39], IR-E: 29.9° [26 – 34], IR-EI: 32.3° [25 – 40]). Subjects in the IR-I group seem to have higher implicit report, although the uncertainty in the estimates is considerable (IR-I: 37.3° [31 – 43]). I n contrast, the exclusion measure was clearly different between the groups (Figure 4B, top left column). Specifically, according to this measure, the CR group showed less implicit knowledge than the other groups (CR: 24.6° [20 – 29], IR-E: 42.0° [37 – 47], IR-EI: 42.9° [35 – 51], IR-I group did not do exclusion) as also reflected in the confidence intervals of the differences between CR and the other two groups (17.3° [8 – 27] and 18.3° [8 – 29]). Thus, it seems that consistent reporting affects the implicit when we measure using exclusion, a fact we might miss when looking at the implicit calculated from the report.

Explicit learning in the CR group, as measured both by subjects' reports and by the explicit exclusion. showed the typical picture with a fast initial rise and a slow drop throughout adaptation (Figure 4A) (Bond and Taylor 2015, McDougle, Bond et al. 2015, Taylor, Krakauer et al. 2014). For the intermittent reporting groups, however, the time course of the reported aiming directions resembled much more that of implicit learning: a slow rise and a stabilization during the last three adaptation blocks (Figure 4A: Time course IR-E, IR-I and IR-EI group). The exclusion explicit also stabilizes in the last three blocks. Reported aiming directions in the last three blocks were similar across groups (Figure 4B, bottom right; CR: 27.3° [20 – 35], IR-E: 22.8° [16 – 30], IR-I: 14.9° [7 – 23] and IR-EI:

22.8° [16 – 30]), indicating that consistent reporting does not enhance awareness as measured by the reporting itself. However, reporting does lead to greater explicit knowledge when we measure it using exclusion. The reduced exclusion in the CR group (figure 4B, top left) led to a larger estimated explicit knowledge (Figure 4B, bottom left, 34.0° [29 – 39]) when compared to the estimated explicit knowledge for subjects in the IR-E (12.5° [7 – 18]) and the IR-EI group (14.7° [4 – 25]). The confidence intervals of the differences indicated a difference of at least 7° and up to 30° between the groups (21.6° [10 – 32] and 19.4° [7 – 31]).

Intermittent measures IR-EI group

Subjects in the IR-EI group performed the entire awareness test intermittently and also performed a final awareness test. To this end, we used a shortened version of the test at the end of each adaptation block in order to obtain the intermittent awareness index. This intermittent AI enabled us to compare the different measures with each other within the same group. For this comparison, we used the normalized intermittent measures (described in the methods). Subjects showed more explicit knowledge when measured by the report (0.4 [0.2 – 0.5]) than by explicit exclusion (0.2 [0.1 – 0.3]) and the intermittent AI (0.0 [-0.1 – 0.1]; Figure 5). However, it is worth noting that the confidence interval of the difference between report and explicit exclusion did include 0 (0.1 [-0.1 – 0.4]) while that of the difference between report and intermittent AI (0.4 [0.1 – 0.6]) did not. We did not find any differences between the different implicit measures.

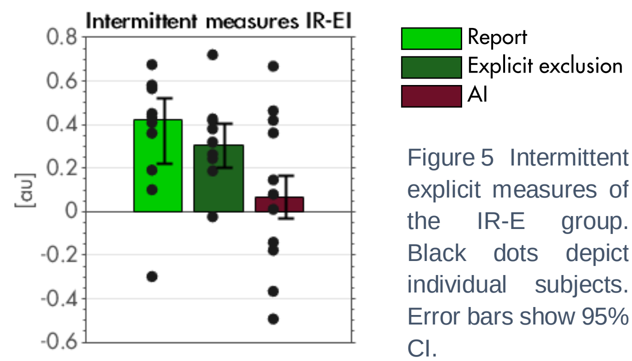


Figure 5 Intermittent explicit measures of the IR-E group. Black dots depict individual subjects. Error bars show 95% CI.

Final measures

Our final measures consisted of the Process dissociation procedure, which consisted of inclusion and exclusion blocks at the end of adaptation. Since subjects had experienced exclusion and/or inclusion intermittently (depending on the group), we expected these measures to produce similar results also in the final test. However, this was not the case. In order to elucidate these dissimilarities as clearly as possible, we will describe inclusion and exclusion separately before presenting the results for the AI and UAI. In Figure 6, we show the different final measures per group. Notably, the final exclusion is similar across groups (Figure 6A and B; CR: 31.1° [24 – 38], IR-E: 31.2° [25 – 37], IR-I: 36.3° [29 – 43] and IR-EI: 35.3° [28 – 42]), which stands in contrast to our findings in the intermittent measures during adaptation. In order to explore the origin of this discrepancy between intermittent and final exclusion, we looked at the differences between the intermittent and final measures. We did find a difference between intermittent and final estimates of exclusion (Figure 7; $F_{(3,2)} = 10.6$ [4 – 27]). Interestingly, the differences between intermittent and final exclusion was negative for the CR group (Figure 7; -6.4° [-15 – -2]) while it was positive for the IR-E (10.8° [3 – 19]) and IR-EI group (4.8° [-6 – 12]), indicating that subjects in the CR group gained implicit knowledge after adaptation

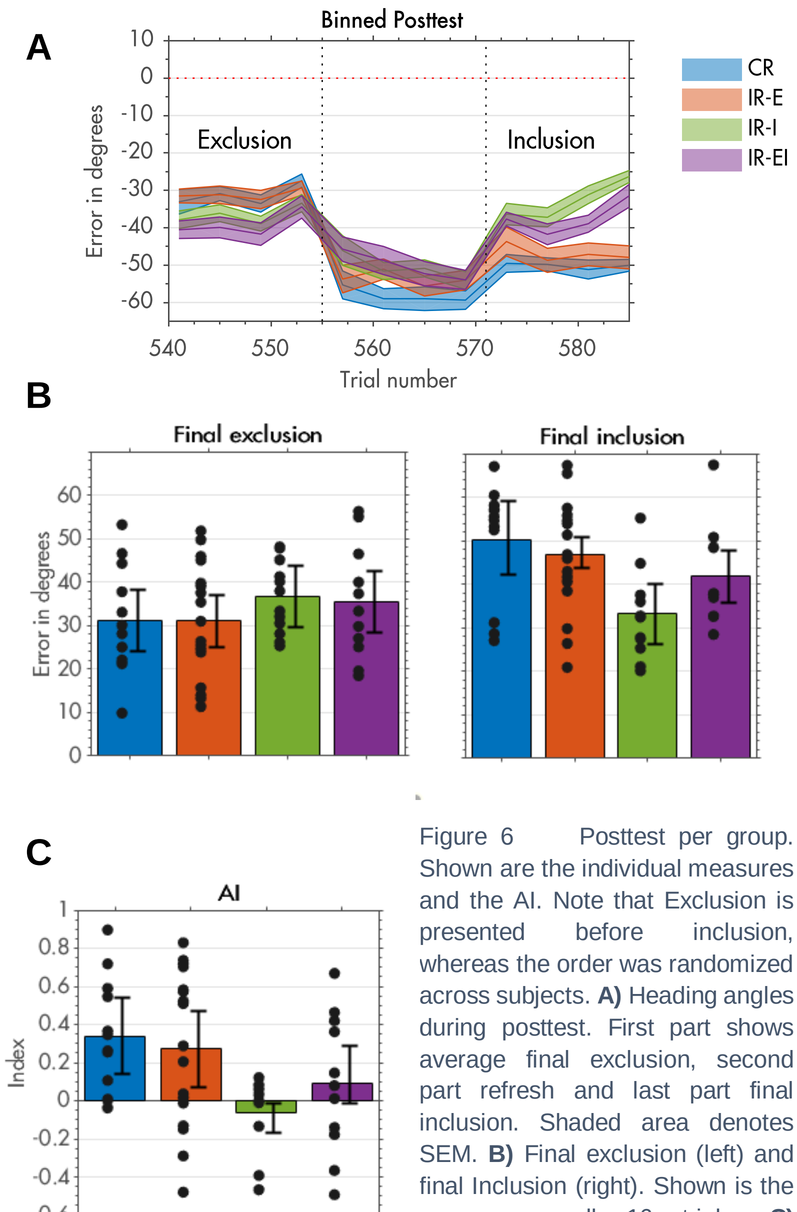


Figure 6 Posttest per group. Shown are the individual measures and the AI. Note that Exclusion is presented before inclusion, whereas the order was randomized across subjects. **A)** Heading angles during posttest. First part shows average final exclusion, second part refresh and last part final inclusion. Shaded area denotes SEM. **B)** Final exclusion (left) and final Inclusion (right). Shown is the mean per all 16 trials. **C)** Awareness Index (AI), which is derived from the final exclusion and inclusion. Black dots depict individual subjects. Error bars show 95% CI.

while subjects in the IR-E and IR-EI group lost implicit knowledge. This difference between intermittent and final amounts of implicit knowledge may be a result of the time delay between the final test trials and the process dissociation procedure. Each group received a short instruction about the last block just after the last test trials at the end of adaptation (+/- 2 min.). This stands in line with previous reports about the implicit process consisting of two underlying components including one that is thought to be time-dependent (labile) and the other time-independent (stable)(Miyamoto, Wang et al. 2014, Morehead 2018).

The final inclusion presented us with a different picture. As mentioned in the methods ('Awareness and Unawareness Indices'), the difference between inclusion and exclusion provides a separate, cleaner, measure of explicit knowledge than the exclusion taken on its own. If subjects are able to reproduce what they did during adaptation, they are more likely to also have more explicit knowledge about the perturbation. Our results reflect this idea: subjects in the IR-I group showed the lowest values for the final inclusion (Figure 6B; IR-I: 32.8° [26 – 40]), followed by subjects in the IR-EI group (43.1° [37 – 49]). The CR and IR-E group showed similar (and higher) values and were able to include almost fully (Figure 6B; CR: 50.2° [42 – 59] and IR-E: 46.9° [40 – 54]). This stands in line with our intermittent results for the implicit report, where the IR-I group showed slightly more implicit knowledge than the other groups (Figure 4 B, top right).

Finally, our results for the UAI and the AI reflect our findings described in the previous paragraph. In line with our results of the final exclusion (see previous paragraph), the four groups showed similar values for the UAI (0.6 [0.4 - .08], 0.5 [0.4 – 0.7], 0.7 [0.6 – 0.8] and 0.6 [0.5 – 0.8] for the CR, IR-E, IR-I and IR-EI group respectively). The AI, on the other hand, differed between groups showing the same pattern as the final inclusion where subjects in the CR and the IR-E group had more awareness (Figure 6D; CR: 0.3 [0.1 – 0.5] and IR-E: 0.3 [0.1 – 0.5]), than subjects in the IR-I and IR-EI group (Figure 6D; -0.1 [-0.2 – 0.1] and 0.1 [-0.1 – 0.3]). However, differences are small and should not be over-interpreted.

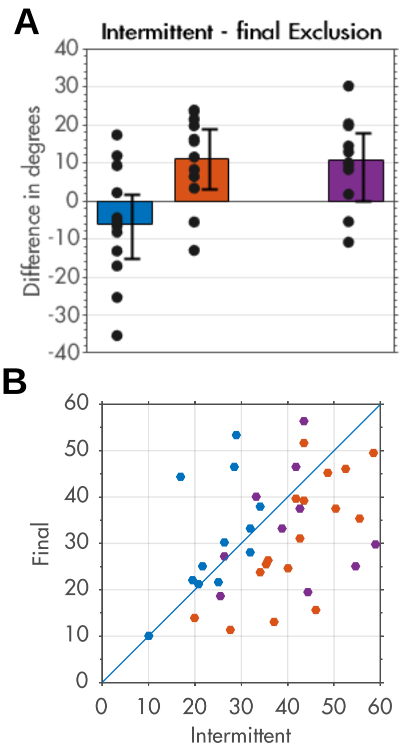


Figure 7 Differences between intermittent and final exclusion for CR, IR-E and IR-EI group. No values are shown for the II group as subjects in this group did not perform any intermittent exclusion. **A)** Bar plots for the differences. Black dots depict individual subjects. Error bars show 95% CI. **B)** Scatter plot of differences.

Lastly, we looked at the correlation across subjects of the three measures we used for both the explicit and implicit component in each group (Table 1). With these correlations, we wanted to assess the congruity of the measures with each other on an individual basis, which would give us a further indication of whether these measures actually capture the same underlying processes. Generally, correlation between measures were relatively high. **Error! Reference source not found.** presents example scatter plots of CR and IR-E groups for explicit exclusion vs reports (**Error! Reference source not found.**A) and exclusion vs implicit report (**Error! Reference source not found.**B). While for the implicit measures correlations were high overall, we suggest that correlations were overall higher for the CR group as compared to the other groups for the explicit measures.

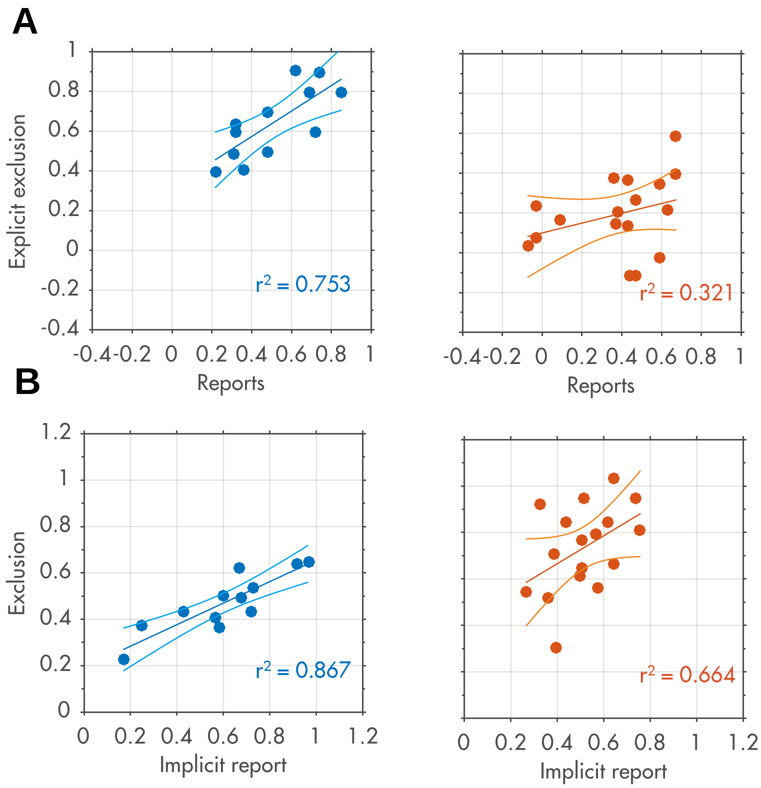


Figure 8 Scatter plots of relation between **A)** Explicit exclusion and reports and **B)** Exclusion and implicit reports for the CR (left column) and the IR-E group (right column).

CR	Report	Explicit exclusion	AI		Report implicit	Exclusion	UAI
Report		0.753	0.587	**Report implicit**		0.867	0.679
Explicit exclusion	0.753		0.693	**Exclusion**	0.867		0.676
AI	0.587	0.693		**UAI**	0.679	0.676	
IR-E							
Report		0.321	0.469	**Report implicit**		0.618	0.478
Explicit exclusion	0.321		0.650	**Exclusion**	0.618		0.664
AI	0.469	0.650		**UAI**	0.478	0.664	
IR-I							
Report			0.574	**Report implicit**			0.459
Explicit exclusion				**Exclusion**			
AI	0.574			**UAI**	0.459		
IR-EI							
Report		-0.111	0.109	**Report implicit**		0.448	0.647
Explicit exclusion	-0.111		0.553	**Exclusion**	0.448		0.646
AI	0.109	0.553		**UAI**	0.647	0.646	

Table 1 Correlations between implicit and explicit measures per group. Shown are r^2 values per pair-wise comparison. The left half shows correlations for the explicit measures (report, explicit exclusion and AI), the right half shows correlations for the implicit measures (report implicit, exclusion, UAI). Note that subjects in the IR-I group did not perform exclusion trials, accordingly no measure for the explicit exclusion was performed and only the correlation between AI and report and UAI and report implicit are presented.

Discussion

We set out to compare different kinds of measures of the explicit and implicit processes with each other in order to: 1) see whether these measures provide the same answers and thus reflect the same underlying processes; and 2) assess the effect of reporting on adaptation and on the measures themselves. We used one direct measure, reporting, and two indirect measures, exclusion and process dissociation procedure. The direct measure differs from the indirect measures in that it measures verbalizable knowledge as opposed to the ability to intentionally control our behavior. Defining explicit knowledge as the knowledge which we can express is common in the cognitive literature (Reber 1967, Nissen and Bullemer 1987), however the alternative definition – explicit knowledge is the ability to control our own behavior – is also in broad use (Jacoby 1991, Destrebecqz and Peigneux 2005). The two indirect measures we used in this study also differ from each other. The process dissociation procedure is an elaboration of the exclusion measure designed to address the uncomfortable fact that when people are asked to exclude and then go back to their previous behavior, they are not always able to do so. Thus, explicit knowledge measured as the ability to control behavior may be contaminated by implicit processes that are revealed by testing the ability to reverse this process.

As discussed in the introduction, assessment through verbal report may also be contaminated by the observer paradox. In order to control for this, we compared two conditions: consistent reporting and intermittent reporting. We had one consistent reporting group (CR), which also performed intermittent exclusion trials, and three intermittent reporting groups who performed exclusion trials (IR-E), inclusion trials (IR-I) or both exclusion and inclusion trials (IR-EI). Performing both inclusion and exclusion trials provides a full process dissociation procedure as used by Werner et al. (2015). Our results show that reporting of the intended aiming direction increases explicit knowledge, but this increased explicit knowledge is not actually reflected in the reporting (Figure 4B & C). However, exclusion trials did reveal the added explicit knowledge driven by consistent reporting. We believe that explicit knowledge was indeed increased in the CR group. Subjects in the CR group adapted faster and were able to counter the perturbation fully compared to subjects in the intermittent groups (Figure 3B). This suggests that the explicit knowledge revealed by exclusion trials contains components that are not measured by verbal reporting. Interestingly, in the CR group, the amount of explicit knowledge measured by both reporting and exclusion is the same (Figure 4C bottom, blue dots). However, in the IR groups, exclusion shows less explicit learning than report (Figure 4C bottom, orange and purple dots). The process dissociation procedure, which provides a cleaner measure of explicit knowledge than the exclusion measure, suggests that exclusion may even be underestimating the discrepancy in explicit knowledge between the CR group and the IR groups (Figure 5).

The report and exclusion show complementary effects on implicit knowledge to those on explicit knowledge. The amount of implicit knowledge in the CR group is the same according to both measures (Figure 4C top, blue dots) and the same as the implicit knowledge in the IR groups as measured by the report (Figure 4B top). However, the IR groups show more implicit knowledge measured by exclusion than they do in the report (Figure 4C top, orange and purple dots).

Discrepancies between estimates of implicit learning measured by report and measured by exclusion (or aftereffect) have been previously reported (Bond and Taylor 2015, Leow, Gunn et al. 2017). Bond et al. (2015) looked at multiple different paradigms all of which involved consistent reporting. In a number of these, aftereffect showed less implicit knowledge than report, although the effects were not large. The direction of these effects is the opposite from our own, where implicit knowledge was more measured by exclusion than measured by report in the IR groups. Leow et al. (2017) compared reporting and non-reporting groups. Their results are congruent with ours: the aftereffect shows more implicit knowledge in the non-reporting group than in the reporting group. However, they could not compare the report measure between the groups since they did not obtain any intermittent reports in their non-reporting group.

The situation is more complicated when comparing to the posttest. In the posttest, differences in exclusion between groups are no longer pronounced. This may be the result of the break between the end of adaptation and the posttest. This could arise, again, from having multiple components. It has been suggested that implicit adaptation is composed of stable and labile components, an idea that has some support in the literature (Miyamoto, Wang et al. 2014, McDougle, Bond et al. 2015, Morehead 2018).

The dissociation that intermittent reporting causes in explicit knowledge as measured by report and exclusion seems to indicate multiple underlying explicit processes. The fact that consistent reporting affects exclusion but not report may shed some light on what these underlying processes might be. One explanation is that reporting may drive what cognitive scientists refer to as metacognition or self-monitoring (Chalmers 1995, Dehaene and Naccache 2001, Dehaene, Changeux et al. 2006, Block 2007). Reporting primes subjects that re-aiming is beneficial (Holland, Codol et al. 2017, Leow, Gunn et al. 2017) by directing subjects' attention to explicitly assess the contents of their experience. This may preferentially drive our ability to control (rather than verbalize) because this process is thought to involve second-order systems that monitor internal signals in order to regulate behavior (Dehaene, Changeux et al. 2006).

Another possibility is that reporting provided subjects with more time to evaluate the perturbation more thoroughly and mentally rotate the visual scene (McDougle and Taylor 2019). This increased ability to do mental rotation may well have increased control without providing better verbalizable knowledge. Previous studies have shown that restricting preparation time may probe implicit processes by suppressing expression of explicit contributions, and, correspondingly, longer reaction times may lead to more explicit knowledge (Fernandez-Ruiz, Wong et al. 2011, Haith, Huberdeau et al. 2015, Leow, Gunn et al. 2017). Haith et al. 2015 showed a larger aftereffect after short preparation time trials than after trials with long preparation times, confirming that more preparation time may lead to more controllable explicit knowledge. Leow et al. 2017 compared two non-reporting groups, one of which had 1000 ms preparation time (long no-report) and the other had 250 ms (short no-report), with a reporting group. Their results are inconsistent with the hypothesized effects of reaction time: the reporting group shows decreased implicit knowledge as measured by the aftereffect, while the long no-report group does not.

Finally, we want to note that we have assumed throughout this paper that the aftereffect and the exclusion measure similar things. However, since these two measures differ in the instructions given to subjects, they may not capture the exact same process or component. Direct comparison between these two measures and their associated instructions is necessary in order to ensure both measures refer to the same processes.

In summary, our results show that different methods may capture different processes and moreover, measurement may confound estimates of explicit and implicit knowledge. We suggest that the AI as a measure provides additional information about subjects' explicit knowledge as it considers the possible contamination of explicit knowledge by implicit influences. It captures an explicit component that does not fully overlap the verbalizable component measured by report. Methodological and theoretical developments are needed to feel we are fully understanding how these components combine to produce reaching movements. We need a new, updated model of the explicit and implicit processes during adaptation.

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Conflict of interest statement

No conflicts of interest, financial or otherwise, are declared by the authors.

References

Amrhein, V., S. Greenland and B. McShane (2019). Scientists rise up against statistical significance, Nature Publishing Group.

Benson, B. L., J. A. Anguera and R. D. Seidler (2011). "A spatial explicit strategy reduces error but interferes with sensorimotor adaptation." J Neurophysiol **105**(6): 2843-2851.

Block, N. (2007). "Consciousness, accessibility, and the mesh between psychology and neuroscience." Behavioral and brain sciences **30**(5-6): 481-499.

Bond, K. M. and J. A. Taylor (2015). "Flexible explicit but rigid implicit learning in a visuomotor adaptation task." J Neurophysiol **113**(10): 3836-3849.

Chalmers, D. J. (1995). "The puzzle of conscious experience." Sci Am **273**(6): 80-86.

Cleeremans, A., A. Destrebecqz and M. Boyer (1998). "Implicit learning: News from the front." Trends in cognitive sciences **2**(10): 406-416.

Dehaene, S., J.-P. Changeux, L. Naccache, J. Sackur and C. Sergent (2006). "Conscious, preconscious, and subliminal processing: a testable taxonomy." Trends in cognitive sciences **10**(5): 204-211.

Dehaene, S. and L. Naccache (2001). "Towards a cognitive neuroscience of consciousness: basic evidence and a workspace framework." Cognition **79**(1-2): 1-37.

Destrebecqz, A. and A. Cleeremans (2001). "Can sequence learning be implicit? New evidence with the process dissociation procedure." Psychonomic bulletin & review **8**(2): 343-350.

Destrebecqz, A. and P. Peigneux (2005). "Methods for studying unconscious learning." Progress in brain research **150**: 69-80.

Fernandez-Ruiz, J., W. Wong, I. T. Armstrong and J. R. Flanagan (2011). "Relation between reaction time and reach errors during visuomotor adaptation." Behavioural brain research **219**(1): 8-14.

Gaillard, V., A. Cleeremans and A. Destrebecqz (2014). "Dissociating conscious and unconscious learning with objective and subjective measures." Clinical EEG and neuroscience **45**(1): 50-56.

Haith, A. M., D. M. Huberdeau and J. W. Krakauer (2015). "The influence of movement preparation time on the expression of visuomotor learning and savings." J Neurosci **35**(13): 5109-5117.

Hegele, M. and H. Heuer (2010). "Implicit and explicit components of dual adaptation to visuomotor rotations". Consciousness and Cognition, **19**, 906–917.

Heuer, H. and M. Hegele (2011). "Generalization of implicit and explicit adjustments to visuomotor rotations across the workspace in younger and older adults." J Neurophysiol **106**(4): 2078-2085.

Heuer, H. and M. Hegele (2015). " Explicit and implicit components of visuo-motor adaptation: An analysis of individual differences. " Consciousness and Cognition **33**, 156-169.

Holland, P. J., O. Codol and J. M. Galea (2017). "The role of explicit strategies during reinforcement-based motor learning." bioRxiv: 234534.

Huberdeau, D. M., J. W. Krakauer and A. M. Haith (2015). "Dual-process decomposition in human sensorimotor adaptation." Curr Opin Neurobiol **33**: 71-77.

Hwang, E. J., M. A. Smith and R. Shadmehr (2006). "Dissociable effects of the implicit and explicit memory systems on learning control of reaching." Experimental brain research **173**(3): 425-437.

Jacoby, L. L. (1991). "A process dissociation framework: Separating automatic from intentional uses of memory." Journal of memory and language **30**(5): 513-541.

Leow, L. A., R. Gunn, W. Marinovic and T. J. Carroll (2017). "Estimating the implicit component of visuomotor rotation learning by constraining movement preparation time." J Neurophysiol **118**(2): 666-676.

McDougle, S. D., K. M. Bond and J. A. Taylor (2015). "Explicit and Implicit Processes Constitute the Fast and Slow Processes of Sensorimotor Learning." J Neurosci **35**(26): 9568-9579.

McDougle, S. D. and J. A. Taylor (2019). "Dissociable cognitive strategies for sensorimotor learning." Nat Commun **10**(1): 40.

Miyamoto, Y. R., S. Wang, A. E. Brennan and M. A. Smith (2014). "Distinct forms of implicit learning that respond differentially to performance errors and sensory prediction errors." Translational and Computational Motor Control (TCMC).

Morehead, J. R. (2018). "Implicit visuomotor adaptation has temporally stable and labile components." 28th Annual Meeting of the NCM Society.

Morehead, J. R., J. A. Taylor, D. E. Parvin and R. B. Ivry (2017). "Characteristics of Implicit Sensorimotor Adaptation Revealed by Task-irrelevant Clamped Feedback." J Cogn Neurosci **29**(6): 1061-1074.

Newell, B. R. and D. R. Shanks (2014). "Unconscious influences on decision making: A critical review." Behavioral and Brain Sciences **37**(1): 1-19.

Nissen, M. J. and P. Bullemer (1987). "Attentional requirements of learning: Evidence from performance measures." Cognitive psychology **19**(1): 1-32.

Reber, A. S. (1967). "Implicit learning of artificial grammars." Journal of verbal learning and verbal behavior **6**(6): 855-863.

Taylor, J. A. and R. B. Ivry (2011). "Flexible cognitive strategies during motor learning." PLoS Comput Biol **7**(3): e1001096.

Taylor, J. A. and R. B. Ivry (2013). "Implicit and explicit processes in motor learning." Action science: 63-87.

Taylor, J. A., J. W. Krakauer and R. B. Ivry (2014). "Explicit and implicit contributions to learning in a sensorimotor adaptation task." J Neurosci **34**(8): 3023-3032.

Timmermans, B. and A. Cleeremans (2015). "How can we measure awareness? An overview of current methods." Behavioural methods in consciousness research: 21-46.

Werner, S., B. C. van Aken, T. Hulst, M. A. Frens, J. N. van der Geest, H. K. Struder and O. Donchin (2015). "Awareness of sensorimotor adaptation to visual rotations of different size." PLoS One **10**(4): e0123321.