



Unconscious cultural cognitive biases in explicit processes of visuomotor adaptation



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Studies have shown that explicit strategies make a significant contribution to visuomotor adaptation. However, little attention has been given to potential unconscious cognitive biases in these strategies, despite that they involve a sequence of cognitive decision-making processes. To reveal the possible cultural biases involved in motor learning, we compared Norwegian and Japanese participants in a visuomotor adaptation task using a verbal report paradigm. The results showed that Japanese participants aimed at locations more deviant from the target to account for rotated visual feedback. Additionally, a greater proportion of Japanese participants changed their aiming direction more frequently than Norwegian participants, even after successfully hitting the target. However, both groups showed similar behavioral performance, with comparable reaching accuracy and aftereffect amplitudes. These results suggest that the explicit component, which is estimated based on verbal reports, includes cognitive biases. The present study challenges the assumption of universality of motor learning among cultures.

In general, strategies help us to achieve better performance when we learn something new. Motor learning is a typical example. It has long been known that the use of explicit instructions as strategies for target actions improves motor performance in training, especially in sports and the rehabilitation of motor deficits^{1–4}. However, it is questionable whether the effects of explicit strategies on motor learning are universal in humans. There are two reasons for this. First, motor learning itself is affected by the characteristics of a particular population, such as aging individuals^{5–8} or subjects with brain deficits^{9–13}. Second, the cognitive processing required to interpret explicit strategies often involves cognitive biases, which in turn rely on decision-making approaches highly dependent on a culture. In fact, cultural and social psychology studies have reported different cognitive biases and explicit strategies in decision making across cultures^{14,15}. In motor learning literature, a recent study employed a machine learning approach on large-scale data and built a predictive model. The study suggested that racial origin might be associated with variations in both implicit and explicit processes of motor learning¹⁶. However, with this exception, motor learning studies have tacitly assumed universality in the use of explicit strategies in motor learning across cultures. To the best of the authors' knowledge, potential cross-cultural variations in motor learning processes have not yet been fully explored. The present study aimed to test the possibility that explicit strategies are influenced by unconscious cognitive biases inherent to the participants' culture. To this end, we applied a visuomotor adaptation

paradigm, a framework used to study how individuals adjust their movements in response to changes in visual feedback to achieve the desired outcome, to participants from two different cultures and examined their use of explicit strategies.

The methodology employed to achieve this goal relies on the operational differentiation of explicit and implicit processes. In this regard, it is important to highlight that both explicit and implicit processes are involved in how visuomotor adaptation takes place^{17–24}. Visuomotor adaptation is considered to be an implicit learning process^{5,17,22,25} because an individual can achieve it without being aware of changes in the environment^{26,27}. This, of course, does not necessarily mean that movement errors cannot be reduced by using explicit strategies, which the participants use to compensate for visuomotor rotation. In an environment where a visuomotor rotation of 30° clockwise is imposed, movement errors can be reduced by intentionally aiming 30° counterclockwise from the visually perceived target. One of the approaches used to investigate the effect of explicit strategies on visuomotor adaptation is to compare a group of participants receiving information about how to compensate for the rotational transformation with another group not receiving explicit knowledge of the rotation. Mazzoni and Krakauer¹⁷ showed that while the strategy-use group quickly reduced the movement error, they were not able to maintain this level of performance, but rather their movement error gradually increased in the later adaptation phase. These results suggest that the participants achieved

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implicit learning while using the strategy. Taylor and Ivry²² conducted an experiment with extended practice to answer the question of whether using explicit strategies over a longer period of time changed the participants' performance. They found that in the strategy-use group, movement errors increased in the later stage of adaptation and then eventually decreased with further practice. Such characteristic learning curves shown in these studies suggest that both explicit and implicit processes operate in parallel and contribute to visuomotor adaptation.

Another approach to quantifying the contribution of explicit strategies to visuomotor adaptation was proposed by Taylor et al.²⁸, who measured the explicit adaptation process through participants' verbal reports. In their experiment, participants performed an aiming task in an environment with a 45° rotational transformation. On each trial in the phase during which the participants learned rotational transformations, they verbally reported the specific landmark number they intended to hit with the cursor from among all the other numbers displayed around the target. The explicit strategies (i.e., verbal responses) were evaluated by the reported landmark number in angle, and it was assumed that the residual value resulting from subtracting the reported landmark number in angle from the movement error in angle was the component reflecting the implicit adaptation process^{28,29}. Figure 1a shows an example of the cursor trajectory when implicit learning has developed to a certain extent while performing the aiming task with verbal reports. Taylor and colleagues showed that participants changed their aiming direction exploratorily in the early phase of learning and gradually began to aim in the same direction in the late phase. On the other hand, the

inferred implicit adaptation process improved slowly and monotonically. The study established an experimental paradigm that delineates implicit learning in a subtractive manner and concluded that explicit and implicit adaptation processes have different temporal characteristics.

In the present study, by comparing the visuomotor adaptation performance of a group of Norwegian and Japanese university students, we aimed to clarify whether the cognitive processes underpinning explicit strategies in motor learning are modulated differently by unconscious biases related to cultural groups. The rationale for this proposal is based on previous studies in cultural psychology, which suggest that socialized implicit norms and values of certain individuals or social groups influence cognitive processes. In Asian cultures, individuals tend to attribute their failures to their own internal factors^{30–32} (for a review, see in ref. 33). Likewise, they place more importance on dialectical and empirical knowledge than on detailed analytical categorization of an event^{32,34}. Thus, in contrast to Westerners, East Asians are more strongly motivated by their failures than by their successes when guiding their actions³⁴. Based on these findings, we predict that Japanese participants will be more likely to change their aiming direction after failing to hit a target than Norwegian participants. However, due to the lack of relevant cross-cultural data on motor control, we cannot make a specific prediction as to which group would show a greater amount of explicit aiming. Nevertheless, given the documented disparities in cognitive processes across cultures^{30–34}, it is anticipated that specific group variations will be identified in components of the motor learning process, particularly in instances where cognitive processing is required. For

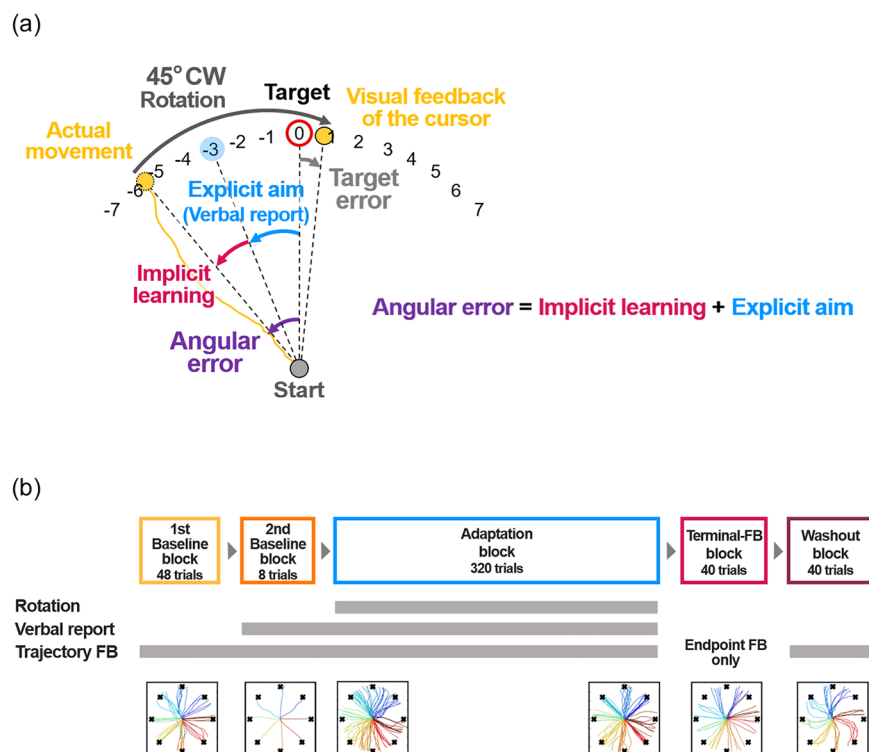


Fig. 1 | Aiming task. a Performance measures. This panel assumes that the participant aimed at −3 (a blue filled circle) and that the cursor's visual feedback (a yellow filled circle with a solid black line) moved roughly in the direction of 1, while the actual movement trajectory was the yellow line. The implicit learning measure was calculated as the deviation between the actual trajectory (i.e., angular error) and the aiming direction (explicit aim). **b** The experimental design and movement trajectories in each block of a typical participant. The movement trajectories are distinguished by different colors according to the different targets aimed at. Only in the adaptation block, 45° clockwise rotation was added to the direction of cursor movement. In the second baseline block and the adaptation block, participants verbally reported their aiming direction before starting an aiming movement on each trial. In all blocks except the

terminal-feedback block, the trajectory and endpoint feedback were always provided. In the terminal-feedback block, visual feedback of the trajectory was removed, and participants could only receive the endpoint feedback. As illustrated by the example trajectory, the participants were able to make straight target-directed movements in the first and second baseline blocks. In the adaptation block, the trajectory curved in the direction of the rotation at first, and participants corrected their movement toward the targets, but they were able to reach the targets at the end of the adaptation block. In the terminal feedback block, the trajectory shifted in the opposite direction of the rotation. When trajectory feedback was restored in the washout block, the participants were able to reach the targets by correcting their movements in the same direction of the rotation.

instance, East Asians and Westerners may differ in the amount of explicit components quantified through a cognitive task in a visuomotor adaptation task.

To reach conclusions, we will account for explicit strategies, or so-called *explicit aim*, which reflects explicit adaptation, as well as three types of measures for implicit components of motor learning: *aftereffects*, *residual aftereffects*, and *implicit learning measure*. The aftereffects of 45° visuomotor adaptation were defined as the difference between baseline errors and errors in the terminal-feedback (no rotation, only endpoint feedback) or washout (no rotation and trajectory feedback) blocks after the adaptation block. We differentiated two types of aftereffects: the (normal) aftereffects were computed using the errors of the first trial of the terminal-feedback or washout block, while the *residual aftereffects* were based on the averages of the last five trials of the terminal-feedback or washout blocks. The residual aftereffects (i.e., the extent of aftereffects remaining) are assumed to reflect the strength of newly learned sensorimotor mappings. The implicit learning measure was calculated by subtracting the explicit aim from the angular movement error. Because the implicit components of motor learning are assumed to be universal, the implicit learning measure should be equivalent to aftereffects regardless of the type of computational methods, and thus the values of implicit learning, as reflected by these measures, should be the same across groups. However, assuming that the implicit learning measure is the difference between angular movement error and explicit aim, the implicit learning measure would differ from aftereffects if explicit aim is sensitive to cultural biases. Since the methodology employed to estimate implicit components of motor learning relies on explicit strategies, the present study also aims to scrutinize the indirect impact of possible cultural biases on the implicit components of motor learning.

Finally, as a supplementary analysis to further contribute to the accumulation of knowledge in motor learning research, we examined the results within the framework of the multi-state model proposed by Smith et al.³⁵. This model posits that motor adaptation consists of two processes: a fast process that responds strongly to errors but exhibits rapid forgetting, and a slow process that responds weakly to errors but supports long-term learning. Although the relationship between the multi-state model and the implicit and explicit components remains controversial^{23,35}, we explored their potential concomitance.

Results

In the first baseline block, there were no significant differences between the two groups in the average and the standard deviation of target error (for the average, $t(46) = -1.49$, $p = 0.14$; for the standard deviation, $t(46) = 0.38$, $p = 0.71$). In the adaptation block, overall, both Norwegian and Japanese groups adapted to a 45-degree visuomotor rotation and showed a stereotypical learning curve^{17,22,28,36} in behavioral task performance (Fig. 2a, b). Initially, the target error decreased rapidly as the participants adapted to the rotation, but over time, the rate of improvement slowed down as the participants approached their performance limit. The performance in the adaptation block, where the participants learned visuomotor rotation, did not significantly differ between the Norwegian and Japanese groups (Fig. 2c). In both groups, the target error decreased in the late period of the adaptation block ($F(1, 46) = 61.11$, $p < 0.001$, $\eta_p^2 = 0.57$). There was no main effect of the cultural group ($F(1, 46) = 1.40$, $p = 0.24$, $\eta_p^2 = 0.03$) and the interaction between the learning phase and the cultural group was not significant ($F(1, 46) = 0.95$, $p = 0.33$, $\eta_p^2 = 0.02$) (see Supplementary Note 2 for details).

Measures for explicit strategies

Explicit aim, a measure calculated by converting the number of landmarks verbally reported by participants into angles, was expected to approach zero as the adaptation to the 45° perturbation develops. It showed significant cultural group effects in both early (the initial 20 trials) and late (the last 20 trials) periods of the adaptation block ($F(1, 46) = 5.66$, $p < 0.05$, $\eta_p^2 = 0.11$). The explicit aim was larger in the Japanese group ($M_{early} = -13.93^\circ$, $SD_{early} = 18.3^\circ$; $M_{late} = -12.91^\circ$, $SD_{late} = 13.0^\circ$) than in the Norwegian group

($M = -6.42^\circ$, $SD = 16.7^\circ$; $M = -2.96^\circ$, $SD = 6.68^\circ$) (Fig. 2c). There was no main effect of the learning phase ($F(1, 46) = 1.31$, $p = 0.26$, $\eta_p^2 = 0.03$) and the interaction between the learning phase and the cultural group was not significant ($F(1, 46) = 0.39$, $p = 0.54$, $\eta_p^2 = 0.01$).

Based on the approach of the previous study²⁸, we also calculated the probability (i.e., the number of participants who changed their aim) and the degree of the aim change (i.e., the difference in aimed landmark numbers in two consecutive trials). These two measures gradually decreased as participants performed the task (Fig. 2a, c). The results showed that the change probability was significantly higher in the Japanese group than in the Norwegian group, *regardless of* whether the cursor had hit the target on the previous trial ($F(1, 46) = 13.34$, $p < 0.001$, $\eta_p^2 = 0.16$), and the probability was also significantly higher when the participants could hit the target ($F(1, 46) = 26.12$, $p < 0.001$, $\eta_p^2 = 0.02$). The interaction between the cultural group and the result of the previous trial was not significant ($F(1, 46) = 0.14$, $p = 0.71$, $\eta_p^2 = 0.0001$), indicating that the effect of trial outcome (miss vs. hit) on the change probability was similar across the two groups (Fig. 3a, b). The overall mean (pooling hit and miss trials) of aim change probability was 26% and 45% in the Norwegian and Japanese groups, respectively. In contrast, the degree of aim change after the ‘miss’ trials was significantly larger than after the ‘hit’ trials in both groups ($F(1, 46) = 31.13$, $p < 0.001$, $\eta_p^2 = 0.36$), and it was larger in the Japanese group ($F(1, 46) = 293.27$, $p < 0.001$, $\eta_p^2 = 0.49$) (Fig. 3c, d). The interaction between the cultural group and the result of the previous trial was not significant ($F(1, 46) = 0.56$, $p = 0.46$, $\eta_p^2 = 0.002$) (see Supplementary Note 3 for detailed results). The differences in the degree of aim change after miss and hit trials were 0.9° for the Norwegian group and 3.5° for the Japanese group. There was no correlation between the degree of error and that of aim change in both groups (for the Norwegian, $r = 0.08$, $p = 0.09$, for the Japanese, $r = 0.13$, $p = 0.23$) (Fig. 3e, f) (see Supplementary Note 4 for results for each participant). Note that eight Norwegian and one Japanese participant always reported aiming at the “0” landmark (the target) in 320 trials of the adaptation block. An additional analysis excluding data from these participants was consistent with the statistical results of the original analysis (see Supplementary Note 5 for details).

Measures for implicit components

The implicit learning measure, calculated by subtracting the explicit aim from the angular error, did not differ significantly between groups. In both groups, the implicit learning measures developed through the adaptation block (Fig. 2a, b) and were larger in the late period than in the early period ($F(1, 46) = 54.48$, $p < 0.001$, $\eta_p^2 = 0.54$). There was no main effect of the cultural group ($F(1, 46) = 1.71$, $p = 0.20$, $\eta_p^2 = 0.04$) and the interaction between the learning phase and the cultural group was not significant ($F(1, 46) = 1.71$, $p = 0.20$) (Fig. 2c). Note that the decrease in aiming angle observed at the end of the adaptation block, when movement errors are small, can coincide with implicit compensation for the visuomotor rotation—that is, adaptation without explicit re-aiming.

To investigate implicit adaptation memory, we evaluated the aftereffects of 45° visuomotor adaptation, defined as the difference between baseline errors and errors in the terminal-feedback or washout block after the adaptation block. Here, we used two types of aftereffects; the (normal) aftereffects were computed using the errors of the first trial of the terminal-feedback or washout block, while the *residual aftereffects* were based on the averages of the last 5 trials of the terminal-feedback or washout blocks to calculate the strength/robustness of implicit memory. The results showed that these measures did not differ significantly between groups (for the aftereffects, $F(1, 46) = 1.07$, $p = 0.31$, $\eta_p^2 = 0.02$; for the residual aftereffects, $F(1, 46) = 0.33$, $p = 0.57$, $\eta_p^2 = 0.01$) (Fig. 4). The aftereffects were larger in the terminal-feedback block than that in the washout block for both groups ($F(1, 46) = 50.44$, $p < 0.001$, $\eta_p^2 = 0.52$), whereas the residual aftereffects were not significantly different between the two blocks ($F(1, 46) = 1.0$, $p = 0.32$, $\eta_p^2 = 0.02$) (see Supplementary Note 6 for further analysis). The interactions between the culture group factor and the block factor were not

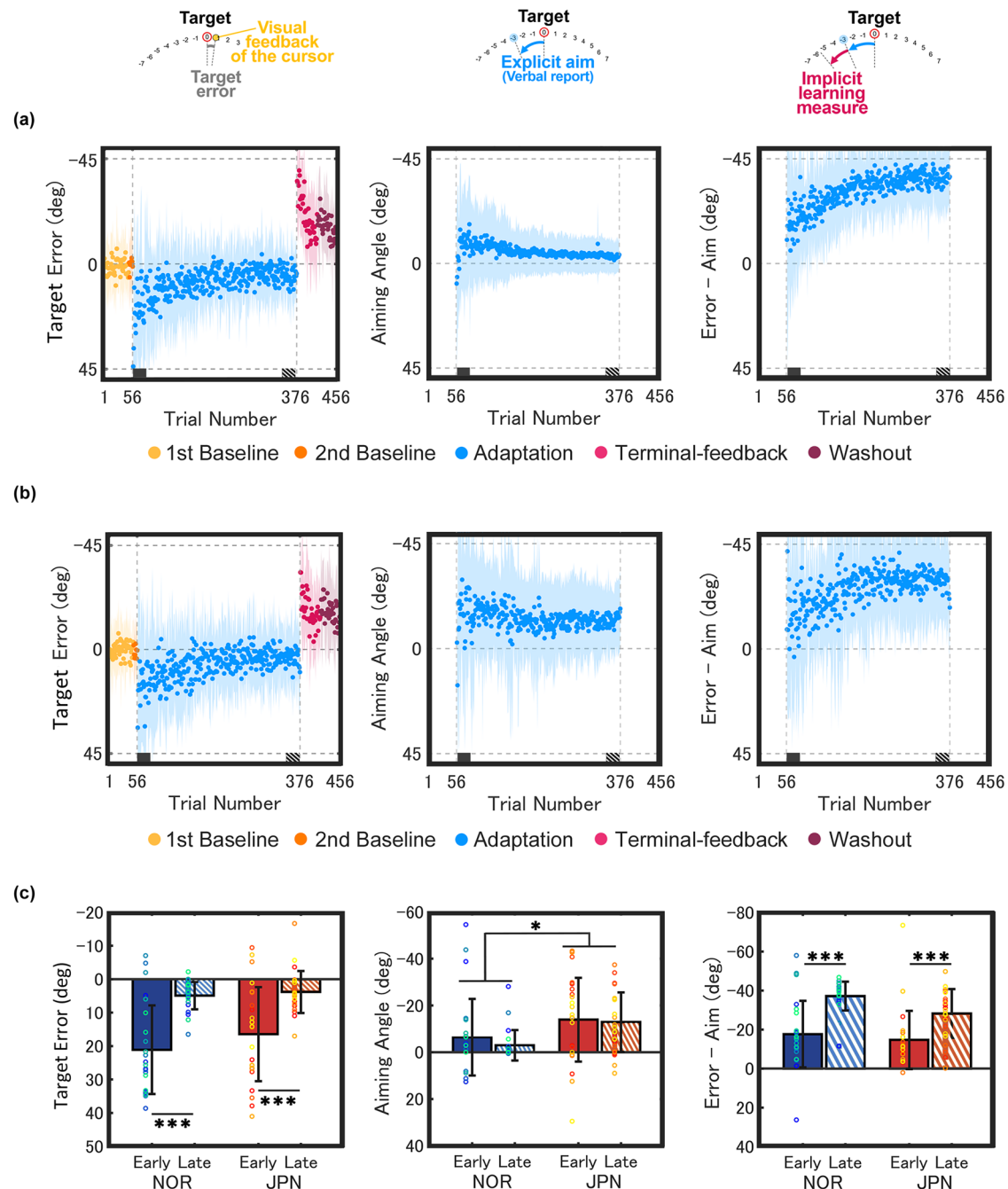


Fig. 2 | Movement performance and adaptation in Norwegian and Japanese groups. Movement performance in the Norwegian group (a) and the Japanese group (b). From left to right, the figures show target error, explicit aim, and implicit learning measure. The horizontal axis represents the number of trials of the aiming task, and the vertical axis represents the magnitude of each measure. The yellow, orange, light blue, pink and purple dots represent the first baseline block, the second baseline block, the adaptation block, the terminal-feedback block, and the washout block, respectively.

The background shading shows the standard deviation of each trial. c Performance at the early and late periods of the adaptation block in both groups. From left to right, the figures show target error, explicit aim, and implicit learning. The early and late periods were defined as the initial 20 trials and the last 20 trials of the adaptation block. The blue bars represent the Norwegian data, and the red bars represent the Japanese data. The dots represent individual data. The error bars show the standard deviation in each period. Single asterisk indicates $p < 0.05$ and three asterisks indicate $p < 0.001$.

significant for both aftereffects and residual aftereffects (for the after-effects, $F(1, 46) = 0.02$, $p = 0.90$; for the residual aftereffects, $F(1, 46) = 0.00$, $p = 0.99$).

Measures based on the multi-state model

We fit the data to the multi-state model³⁷ and showed that there were no significant differences between the Norwegian and Japanese groups in any of the parameter values (Fig. 5). The individual values of the best-fit model parameters were as follows (Table 1): for the fast process, the

learning rate parameters of the Norwegian and Japanese groups were 0.25 ($SD = 0.28$) and 0.36 ($SD = 0.19$), respectively, and the retention parameters were 0.53 ($SD = 0.32$) and 0.63 ($SD = 0.33$), respectively. There were no significant differences in these parameters between the two groups ($t(46) = 1.67$, $p = 0.10$; $t(46) = 1.02$, $p = 0.31$). For the slow process, the learning rate parameters of the Norwegian and Japanese groups were 0.03 ($SD = 0.11$) and 0.04 ($SD = 0.03$), respectively, and the retention parameters were 0.998 ($SD = 0.002$) and 0.999 ($SD = 0.002$), respectively.

Fig. 3 | Aim change probability, magnitude, and its relationship with target error. **a** The probability of aim change in the adaptation block. **b** The probability of aim change calculated according to the results of the previous trial. The error bars show the standard deviation in each group. Three asterisks indicate $p < 0.001$. **c** The aim change in angle. **d** The aim change in angle calculated according to the results of the previous trial. The error bars show the standard deviation in each group. Three asterisks indicate $p < 0.001$. **e, f** The correlations between the target error and the aim change in the next trial for the Norwegian and Japanese participants. The blue dots, the blue and green bars represent the Norwegian data, and the red dots, the red and yellow bars represent the Japanese data. The background shading in Fig. 3a and c and error bars in Fig. 3b, d show the standard deviation in the group.

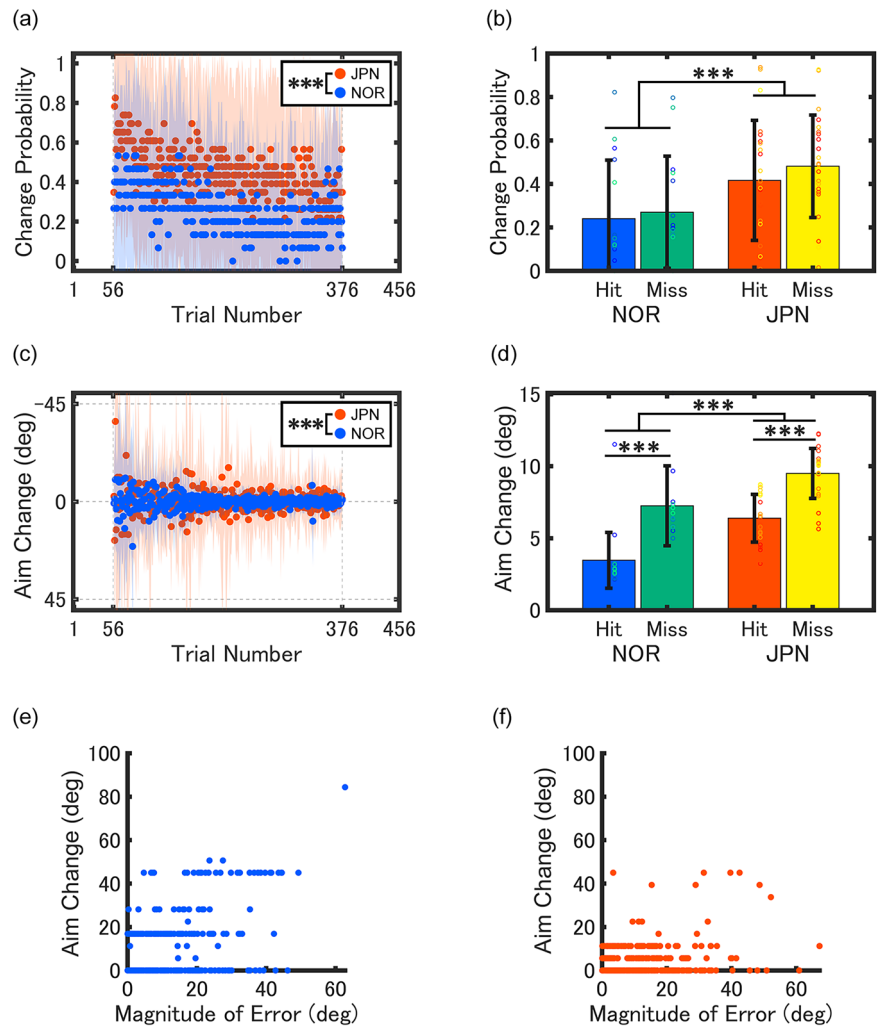
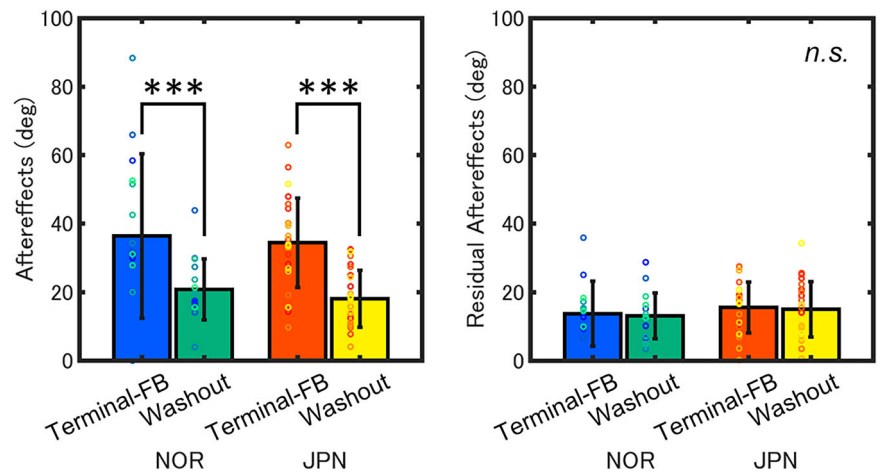


Fig. 4 | The aftereffects (left) and the residual aftereffects (right) in the terminal-feedback and washout blocks. The aftereffects of 45° visuomotor adaptation were defined as the difference between baseline errors and errors in the terminal-feedback or washout block after the adaptation block. The (normal) aftereffects were computed using the errors of the first trial of the terminal-feedback or washout block, while the residual aftereffects were based on the averages of the last five trials of the terminal-feedback or washout blocks. The vertical axis represents the aftereffects and residual aftereffects in angle. The blue bars represent the Norwegian data, and the red bars represent the Japanese data. The dots represent individual data. The error bars represent the standard deviation in each block.



Correlation among measures for implicit components

We conducted correlation analyses to confirm the consistency of the implicit learning measure, the aftereffects, and the estimated parameter values of the slow state of the multi-state model (Table 2), since they are expected to reflect the same universal implicit learning processes. First, the correlation coefficients between the implicit learning measure in the last period of the adaptation block and the aftereffects in the terminal-feedback and washout blocks were not strong in both groups (for

Norwegian, $r = 0.08$, $t(22) = 0.40$, $p = 0.70$; $r = 0.18$, $t(22) = 0.85$, $p = 0.41$, for Japanese, $r = -0.23$, $t(22) = 1.08$, $p = 0.30$; $r = -0.31$, $t(22) = 1.53$, $p = 0.14$). Second, in both Norwegian and Japanese groups, the learning rates of the slow process were not correlated with either the implicit learning measure or the aftereffects in the terminal-feedback block (for Norwegian, $r = 0.13$, $t(22) = 0.60$, $p = 0.56$; $r = 0.05$, $t(22) = 0.25$, $p = 0.81$, for Japanese, $r = -0.16$, $t(22) = -0.75$, $p = 0.46$; $r = -0.04$, $t(22) = -0.20$, $p = 0.84$).

Post-hoc power analysis

Since we did not conduct an a priori power analysis, we performed a post-hoc power analysis on the results of the ANOVAs for the main outcome measures: explicit aim, the probability of aim change, the degree of aim change, implicit learning measure, and aftereffects. The analyses were based on two-way mixed-design ANOVAs (within-between design), reflecting the actual statistical models used in our study. We used the same alpha level ($\alpha = 0.05$) as that employed in the original statistical tests, in order to ensure consistency in the interpretation of the results. The effect sizes were derived from the observed partial eta-squared (η_p^2) values for each analysis. The total sample size included in the analysis was 48 participants, 24 in each group. The resulting post-hoc power estimates indicated adequate sensi-

tivity for most outcomes: 0.64 for explicit aim ($\eta_p^2 = 0.11$), 0.95 for the probability of aim change ($\eta_p^2 = 0.16$), and 1.00 for the degree of aim change ($\eta_p^2 = 0.36$), implicit learning ($\eta_p^2 = 0.54$), and aftereffects ($\eta_p^2 = 0.52$). These results suggest that the sample size used in the present study was sufficient to detect the observed effects in most cases, although power was relatively low for the explicit aim measure.

Post-hoc power analyses were also conducted for the correlation tests reported in Table 2, using a sample size of $n = 24$ in each analysis. The resulting power values were generally low, reflecting the modest sample size and small to moderate effect sizes observed. Specifically, the power to detect the correlation between the implicit learning measure and aftereffects in the terminal-feedback and washout blocks was 0.07 and 0.62, respectively, for the Norwegian group, and 0.19 and 0.31, respectively, for the Japanese group. For the correlations between the learning rate of the slow process and the implicit learning measure or aftereffects in the terminal-feedback block, the corresponding power values were 0.09 and 0.06 in the Norwegian group, and 0.11 and 0.05 in the Japanese group. These results suggest that the absence of significant correlations should be interpreted with caution, as the analyses may have been underpowered to detect small to moderate effects.

Discussion

In the present study, we investigated whether cultural background influences explicit strategies in motor learning by comparing the visuomotor adaptation performance of Norwegian and Japanese university students. Based on previous findings in cultural psychology, we hypothesized that Japanese participants would adjust their aiming direction more frequently following errors than Norwegian participants, reflecting a stronger tendency to learn from failure. However, due to the lack of prior cross-cultural research on motor control, we did not predict which group would exhibit a greater degree of explicit aim. Additionally, since implicit motor learning is considered universal, we expected implicit learning measures to be consistent across groups, unless explicit aim—used to estimate implicit components—was influenced by cultural biases. Through these analyses, we aimed to determine whether cultural differences in cognitive biases indirectly shape implicit motor learning via their impact on explicit strategies.

The present study has two main findings. First, the aiming directions and the aim change probability differed between the two cultural groups (Norwegian vs Japanese), while the implicit learning measure was essentially the same between them. Our prediction on explicit strategies was partially supported, as we predicted that group differences would only be observed after the occurrence of reaching failures. These results highlight a key difference in explicit strategies between the two cultural groups and reinforce our view that explicit strategies in visuomotor adaptation are not universal but rather influenced by unnoticed, culturally shaped cognitive styles. Importantly, however, our findings do not challenge the universality of implicit motor learning processes. Instead, they suggest that methodological factors, such as the way explicit strategies are quantified, may inadvertently introduce variations across populations, making the underlying motor

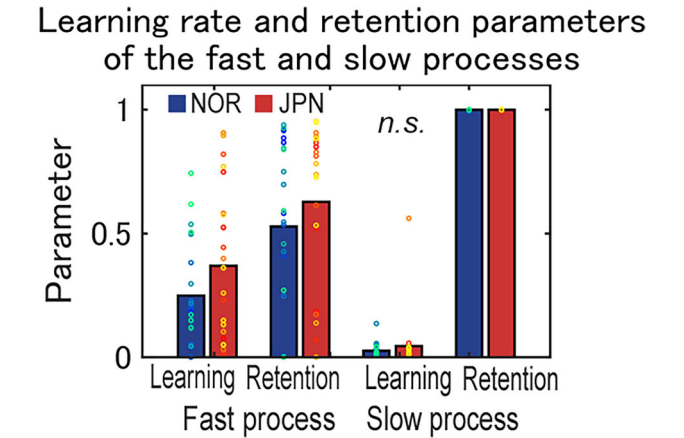


Fig. 5 | The learning rate and retention parameters of the multi-state model. The blue bars represent the Norwegian data, and the red bars represent the Japanese data. The dots represent individual data.

Table 1 | The best-fit model parameters for the multi-state model

		NOR		JPN	
		M	SD	M	SD
Fast process	Learning rate	0.25	0.28	0.36	0.19
	Retention	0.53	0.32	0.63	0.33
Slow process	Learning rate	0.03	0.11	0.04	0.03
	Retention	0.998	0.002	0.999	0.002

The multi-state model proposes two mechanisms to explain human motor learning: the fast process learning, which rapidly reduces errors but also rapidly causes forgetting; and the slow process learning, which reduces errors slowly but also causes forgetting more gradually.

Table 2 | Correlations among measures for implicit components

		Aftereffects in Terminal-FB block		Aftereffects in Washout block		Learning rate of slow process	
		r	95% CI	r	95% Lower CI	r	95% CI
NOR	Aftereffects in Washout block	0.45*	[0.05, 0.72]	—	—	—	—
	Implicit learning measure	0.08	[−0.33, 0.47]	0.18	[−0.24, 0.54]	0.13	[0.29, 0.50]
	Learning rate of slow process	0.05	[−0.36, 0.45]	0.06	[−0.35, 0.46]	—	—
JPN	Aftereffects in Washout block	0.44*	[0.04, 0.71]	—	—	—	—
	Implicit learning measure	−0.23	[−0.58, 0.20]	−0.31	[−0.63, 0.11]	−0.16	[−0.53, 0.26]
	Learning rate of slow process	−0.04	[−0.44, 0.37]	−0.17	[−0.54, 0.25]	—	—

Aftereffects is calculated from the target error, while the implicit learning measure was calculated as the difference between explicit aim and the angular error. The asterisk indicates that the correlation is significant at the 0.05 level.

learning components appear different. Second, the implicit learning measure, calculated as the residual (movement error minus reported aiming direction), did not correlate with aftereffects. As described in the Methods section, aftereffects are a conventional measure of the establishment of implicit motor adaptation to a novel environment^{38–40}. Our results indicate that implicit learning estimates derived from verbal reports do not align with those derived from behavioral errors. These findings underscore the need to reconsider how explicit and implicit components of motor learning are quantified and whether these measures genuinely capture universal aspects of motor learning, as traditionally assumed.

Three results from the present study support the idea that the Japanese participants are more exploratory than the Norwegian participants. First, the Japanese participants showed a higher proportion of aim change (45%) than the Norwegian participants (26%) (Fig. 2b). The aim change probability of our Norwegian participants was similar to that of American university students in a previous study (~25%)²⁷. Second, the mean amplitude of explicit aim (verbal reports) was larger in Japanese than in Norwegian participants, even in the late phase of adaptation. Third, even after hit trials (successes), about 24% of the Norwegian participants and about 42% of the Japanese participants changed their aiming direction. The percentages of aim changes after hit trials reported in the previous study with American participants²⁸ were also similar to those of the Norwegian participants. This type of aim change after a hit trial can be interpreted as an attempt by the participants to make the movement trajectories straighter²⁸. In other words, the two cultural groups may have differed in how they evaluated the success of their explicit strategies, and Japanese participants may have actively changed their explicit strategies even after a successful reaching movement in order to compensate for the rotational transformation and improve their own performance. Taken together, these three results suggest the possibility that cultural differences influence explicit strategies in motor learning.

The present findings conjointly suggest that cognitive factors may influence explicit strategies in motor learning. Typical findings include the influence of knowledge of results^{41–44} and knowledge of performance^{45–47}. Similarly, the effects of age-related cognitive decline on learning have been widely studied^{48–50}. In addition, feedback given during learning^{51,52} and the learner's own motivation and attention⁵³ for review⁵⁴, enhance the magnitude of motor skill learning. Accordingly, it would not be surprising to find culturally dependent cognitive styles modulate the components of motor learning.

The group difference in explicit strategies in the present study could be interpreted based on previous findings in comparative cultural psychology showing the difference in cognitive styles between cultures (see Supplementary Note 1 for details). In the present study, we assumed that Norwegian has cultural traits of Western countries. There is little data on cognitive biases from the perspective of cultural psychology as for the Norwegian sample. However, studies with Norwegian participants, most of which were conducted with pupils and young students⁵⁵, have shown comparable results to those from North American cultures. Previous studies have suggested that individuals from the Japanese culture tend to attribute their failure to their own internal traits rather than to external factors^{30,31}. It is also known that Western cultures are individualistic and have more confidence in their decision-making abilities than individuals from East Asian cultures¹⁴. Based on these cultural differences, we can interpret that Japanese participants in this study may have less confidence in their own decision-making to compensate for visuomotor rotation than Norwegian participants and may be less likely to attribute the success of their reaching movements to their strategy. For this reason, the Japanese participants may have changed their aiming direction more often than the Norwegians.

It is also possible that the Japanese participants exhibited exaggerated movements in order to receive clearer feedback that efficiently modeled the optimal explicit strategies for better performance. It has been known that explicit visual feedback plays a crucial role in refining movement strategies in visuomotor adaptation tasks^{56–58}. Previous studies suggest that East Asian learners, including Japanese individuals, often emphasize external

guidance^{59,60}. In contrast, individuals from Western cultures may rely more on internal confidence in their decision-making processes¹⁴. Given these tendencies, Japanese participants in the present study may have used exaggerated movements to enhance feedback clarity, thereby facilitating more effective strategy refinement.

In contrast to the findings on the explicit adaptation process, the present results suggest that cultural factors do not influence the implicit adaptation process. Regarding adaptation to a novel environment with visuomotor rotation, there was no significant difference between Norwegian and Japanese participants in the implicit learning measure calculated from verbal reports and in the magnitude of (normal) aftereffects. In terms of re-adaptation to the original environment after visuomotor rotation was removed, the aftereffects in the washout block were smaller than those in the terminal-feedback block in both the Japanese and Norwegian groups, and there was no significant difference in the residual aftereffects between the two groups. These results suggest that implicit learning proceeded similarly in the two cultural groups and that they acquired equally robust sensorimotor mappings. Although not the main focus of this study, it is interesting that residual aftereffects were observed not only in the terminal-feedback block but also in the washout block with visual feedback in both the Norwegian and Japanese groups. This result may suggest that the internal model adapted to the novel environment was not fully switched back to the one corresponding to the original environment.

Note that the aftereffects observed in our study (~40°) were larger than those found in previous studies^{22,28} (~30°). Considering that almost all experimental settings and experimental tasks were the same in these previous studies, the larger aftereffect in our study could be attributed to the use of a trackball to control a visual cursor instead of other devices such as digitizing pens^{29,39,61}, a robotic manipulandum^{23,62,63}, or a 3D motion tracking system^{21,64}. We used a trackball to eliminate sensory feedback and motor commands for task-irrelevant motions (e.g., moving the cursor back from the target position to the start position) after the aiming movement, which could provide or distract participants with additional information about the visuomotor rotation. Our experimental setting would have led to the larger aftereffects, as they reflect implicit learning rather than explicit strategies^{38–40}, and less noise or uncertainty in error information leads to greater motor learning⁶⁵. Another possible reason for the larger aftereffects observed in this study is that the length of the break that participants took just before starting the terminal-feedback block was different from that in previous studies. The participants of the present study could take short breaks less than 1 min at any time during trial intervals. The retention of motor memory following adaptation is known to be modulated by the amount of between-trial forgetting⁶⁶. Notably, Kim et al.⁶⁶ demonstrated that forgetting is primarily induced by interference from other motor actions, rather than by longer inter-trial intervals alone. They found that motor memory retention was better in the long inter-trial-interval condition (18.4 s) than in the short inter-trial-interval condition (5.2 s), suggesting that longer pauses without interference can help preserve motor memory. If the participants in this study took a longer break just before measuring the aftereffects, it is undeniable that this may have produced larger aftereffects.

Implicit learning measures may not be associated with aftereffects as long as they are calculated from verbal reports. The three measures of implicit learning (the aftereffects, an implicit learning measure calculated from verbal reports, and the learning rate of a slow process of a multi-state model) in the present study were not correlated with each other. This result is consistent with previous studies that estimated the amount of implicit learning using two types of calculations and found a disparity between implicit measures based on verbal reports and movement errors^{29,62,67–70}. It is also reported that the implicit component calculated based on participants' verbal reports was estimated to be 5° to 17° larger than the aftereffects^{28,29}. While the average implicit learning measure calculated based on verbal reports for Norwegian (early: −15.9°, late: −37.9°) and Japanese (early: −17.6°, late: −25.9°) and the aftereffects for Norwegian (terminal-feedback: 36.9°, washout: 21.4°) and Japanese (terminal-feedback: 33.8°, washout: 17.8°) were comparable in the present study, these two measures did not

correlate with each other (Table 2). As noted in previous studies^{68,69}, the lack of correlation and the discrepancy in the magnitude of the implicit learning measures suggest that the measures reflect different aspects of implicit motor learning.

The present results suggest that performance on motor learning tasks—traditionally quantified as the sum of explicit and implicit components terms in previous motor learning studies^{27,28}—is influenced by factors that can modulate these components. Specifically, we have demonstrated that unconscious cognitive biases, shaped by culture, have a substantial impact on exploratory behavior and certain explicit and implicit learning measures. If such cognitive bias were incorporated into a motor learning model comprising explicit and implicit elements, they would function as a weighting factor on the explicit component. This potential weighting effect must be carefully considered when estimating implicit learning, which is typically inferred through explicit measures rather than observed directly. As with studies on motor learning in older adults^{5–8} and individuals with brain injuries^{9–13}, it is essential to account for participant characteristics, even when studying healthy young adults. Importantly, our findings do not indicate a fundamental flaw in the methodology proposed by Taylor et al.²⁸; rather, they suggest refinements that could enhance its applicability across diverse populations. By revealing the influence of unconscious cognitive biases on motor learning, our results challenge the assumption that explicit strategies in motor learning are universally shared across cultures—a notion that has often remained implicit in the literature. However, we emphasize that this does not contradict the universality of the underlying motor learning processes themselves, but rather underscores the need for careful methodological considerations when interpreting cross-cultural differences.

The present study has several limitations. First, we did not design this study to explore in depth the underlying cultural causes of group differences in motor performance and did not quantitatively measure participants' attitudes, which have been suggested to vary across cultures^{14,30,31}. To further investigate the impact of culturally derived cognitive biases on motor learning, it is necessary to examine participants' self-reported measures of confidence in their own decisions¹⁴ and attributions for the causes of errors^{30,31}. In addition, as explored in a recent study¹⁶, a comparison of multiple racial origins (e.g., Caucasian, multiracial, African American, Asian, and Latinx) might elucidate the effect of cognitive biases on the explicit adaptation process. Second, it appears that the results of 8 out of 24 Norwegian participants, who consistently reported aiming directly at the target during the adaptation block, may explain the much smaller magnitude of explicit aim in their group compared to the previous study²⁸. The present study did not clarify why these participants did not attempt to change their explicit aim. Third, future studies may benefit from examining the impact of variables that were not controlled or explicitly measured in the present study. These include physiological characteristics such as height-related differences in body kinematics, reaction time differences, prior experience with trackball-like devices, and environmental factors such as temperature and season. Additionally, motivational factors, including enjoyment and motivation to participate in experiments, previously identified as potential influencers of motor learning performance¹⁶, should also be explicitly assessed. Given that these variables were neither controlled nor explicitly measured in the present study, it remains possible that they contributed to the observed group differences in motor learning. Addressing these variables in future research would help clarify their potential impact on motor learning performance.

Methods

Participants

A total of 48 university students participated in the experiment, comprising 24 Norwegian students (mean age = 22.8 years, *SD* = 2.4) and 24 Japanese students (mean age = 20.2 years, *SD* = 1.4). The Norwegian students were recruited from UiT The Arctic University in Norway, while the Japanese students were recruited from Waseda University. Prior to the test session, written instructions were displayed on the PC monitor in Japanese for the Japanese group and in English for the Norwegian participants, as the first

author, a Japanese national, oversaw the experiment in Norway. The Japanese experimenter provided oral explanations to the Japanese participants in Japanese, while the Norwegian experimenter offered oral explanations to the Norwegian participants in Norwegian. We ensured that all participants had a clear understanding of the instructions before starting the experiment. The present study was conducted in accordance with the principles expressed in the Declaration of Helsinki. The research project was approved by the Department of Psychology's internal research ethics committee (IPS-REC) at UiT The Arctic University of Tromsø (No.18/R1) and the academic research ethical review committee at Waseda University (No.2018-051). Prior to the experiment, written informed consent was obtained from all participants.

Experimental settings

The experimental settings and design basically followed that of Taylor et al.²⁸. Participants performed an aiming task on a computer display using a trackball mouse (Slimbrade 72327, Kensington Technology Group, USA). We used a trackball mouse because it does not necessarily require moving back to the initial position after a movement, whereas a normal mouse needs to do so, which could provide uncontrolled information about visuomotor rotation and unnecessary visual and proprioceptive feedback. Participants did not need to move their right-hand fingers to prepare for the next trial after completing a reaching movement in the previous trial. This setting allowed us to assess feedforward control at the beginning of each aiming movement. Participants were seated on a chair in front of an upright computer monitor (Philips, 24-inch), which was located at ~60 cm away from their eyes. The experiments were controlled by MATLAB using Psychtoolbox, and the refresh rate of the monitor and the recording rate of the mouse cursor were 60 Hz.

Aiming task

In the experiment, participants were asked to move a cursor on the display to one of the eight targets as quickly and accurately as possible. They were also instructed not to necessarily stop at the target but rather to pass through the target with the cursor. The cursor and targets were displayed as a yellow circle with a radius of 3.5 mm and empty red circles with a radius of 7 mm, respectively. Each trial started when participants pressed the space bar with their left index finger, and the cursor was displayed at a start position, and one of the eight targets was displayed after a random blank between 0 and 1 s. The start position of the cursor was the center of the display, and the locations of the eight targets were arranged on a 7 cm radius from the start position of the cursor at 45 degrees apart. On each trial, participants received audiovisual feedback indicating whether the cursor hit the target or not and whether they moved the cursor at the appropriate speed (less than 500 ms per reaching movement) (Supplementary Note 7).

The experiments consisted of five blocks: first baseline, second baseline, adaptation, terminal feedback, and washout blocks (Fig. 1). In the first baseline block, the participants performed 48 trials of aiming movements without visuomotor rotation. In the second baseline block, the participants practiced an aiming task with verbal reports without rotation. In trials requiring verbal reports, landmark numbers (from −31 to 31) were presented on a circle outside the target position. The targets were placed at a radius of 7 cm from the cursor's starting position, ~5.7 degrees apart. Participants were then asked to report the number they strategically aimed to hit before moving the cursor. The landmark number "0" was always located at the target position of the trial. Positive numbers were located at clockwise direction and negative numbers were at counterclockwise direction from the landmark number "0". The arrangement of the numbers was thus "rotated" on each trial depending on the target position. In the second baseline and adaptation blocks, participants were instructed that they could change their explicit aim (reporting number) from trial to trial. In the second baseline block, the direction of the reported number was supposed to be consistent with that of the presented target, i.e., zero.

In the adaptation block, the participants performed 320 trials of aiming movements with 45 degrees of visuomotor rotation to the clockwise

direction to adapt to the novel environment, and they had to give verbal reports before starting to move the cursor. The verbal reports in the adaptation block were supposed to vary according to the participants' explicit strategies for hitting the targets. Participants were not informed about the degree of the rotation, but they were told that if they found it difficult to move the cursor, it was due to perturbations embedded in the experimental task and not to a malfunction of the trackball. In the terminal-feedback block, where we investigated the final state of the adaptation, participants performed 40 aiming movements without verbal reports. Only the endpoint feedback of the cursor was provided in the terminal feedback block. Participants were informed that the perturbations would be removed and were instructed to aim directly at the target with the cursor without verbal reports. In the washout block, in which we examined re-adaptation to the original environment, participants performed 40 aiming movements without visuomotor rotation, just as in the first baseline block. Before starting the washout block, participants were informed that the condition would be exactly the same with the first baseline block and that no perturbation on the mouse cursor would be applied.

With the exception of the terminal-feedback block, visual feedback of the mouse cursor was available during and after the movement, and feedback of time and accuracy constraints was provided. Participants completed the trials at their own pace and were allowed to take short breaks less than 1 min at any time during trial intervals. The number of trials for each target was the same within a block, and the order of the target presentation was randomized within a block.

Movement analyses

We calculated three measures for each trial in all blocks: target error, movement time, hit rate. Target error was calculated as the difference in angle between a straight line connecting the start point to the target and a straight line between reference points located at 1 and 3 cm along the trajectory²⁸. This range is the initiation of a reaching movement, wherein online correction is not performed. The range from 0 cm to 1 cm was excluded because it was presumed to contain noise immediately following the initiation of the trackball's movement. Movement time was defined as the time from the movement initiation to the time when the cursor exceeded the 7 cm radius from the start. Hit rate was calculated as the percentage of successful hits on the target.

To evaluate explicit strategies and to estimate implicit learning, we calculated explicit aim and implicit learning measure for each trial in the adaptation block, following the analysis of Taylor et al.²⁸. Explicit aim was calculated based on the participants' verbal reports, which were converted to values in degrees. Implicit learning measure was calculated as the difference between explicit aim and angular error. These indices were averaged over the first and last 20 trials of the adaptation block to assess the performance of the early and late learning phases. We also calculated the probability and amount of aim change to evaluate how the participants' explicit strategies changed in the adaptation block. For the probability of aim change, we labeled whether participants changed their aiming direction from one trial to the next with a value of 0/1 and compared how the probability of changing their strategies differed when participants successfully hit the target and missed the target on the previous trial. We also analyzed the aim change in angle separately for whether the participants hit or missed on the previous trial to investigate whether the degree of error on a trial affected the subsequent strategic response.

In addition, we computed aftereffects, a conventional measure of implicit motor learning, which are assumed to reflect the acquisition of a new sensorimotor mapping^{38,71}. In motor adaptation studies, the aftereffects, a movement bias in the opposite direction to the previously imposed perturbation, are observed when the environment changes after the participants have adapted to the previous environment^{39,40}. For example, in visuomotor adaptation tasks, when participants return to a normal environment (rotation is OFF) after adapting to a novel environment (rotation is ON), their movement error increases for a while even though they are perfectly familiar with the normal environment. In the present study, we

calculated the aftereffects in both the terminal-feedback and washout blocks and defined it as the difference in target error between the average of the last eight trials in the first baseline block (the baseline error) and the first trial in the terminal-feedback or washout block. We also calculated residual after-effects, which we assumed to indicate the strength of the learned novel sensorimotor mapping. The calculation was performed by taking the difference between the baseline error and average error of the last eight trials of the terminal-feedback or washout blocks.

Application of the multi-state model to the present data

We exploratively investigated the concomitance between the multi-state model and implicit and explicit components of motor learning. Smith et al.³⁷ modeled two processes to explain human motor learning. A fast process learning reduces errors rapidly, but it forgets rapidly, while a slow process learning reduces errors slowly but forgets slowly. It has been suggested that the fast and slow processes closely resemble explicit and implicit components of learning, respectively^{23,35}. The fast process (x_1) and the slow process (x_2) are combined to produce the net motor output $x(n)$ (Eq. 1). The retention parameter (A) and the learning rate parameter (B) represent the characteristics of the two processes: the fast process learns quickly (B_f) but has poor retention (A_f), while the slow process has better retention (A_s) but learns more slowly (B_s). $e(n)$ represents the error, and ϵ represents the noise, which is proportional to the degree of the error in the previous trial, i.e., the search noise in the explicit strategies. The model is as follows:

$$x = x_1 + x_2 \quad (1)$$

$$x_1(n+1) = A_f \cdot x_1(n) + B_f \cdot e(n) + \epsilon \quad (2)$$

$$x_2(n+1) = A_s \cdot x_2(n) + B_s \cdot e(n) \quad (3)$$

$$A_s > A_f, B_f > B_s \quad (4)$$

We computed confidence intervals around the best-fitting parameter values by bootstrapping model fits to the data. We made 1000 different bootstrap estimates of the data mean, each by averaging data from 14 randomly generated choices made from the 14 participants' data pool with replacement. We fit the model to each of these bootstrap estimates and used the 2.5 and 97.5 percentile values of each parameter as the limits of the 95% confidence interval.

Statistical analysis

We performed the following four analyses. First, a two-way mixed ANOVA was conducted for target error, movement time, hit rate, explicit aim, and implicit learning measure in the adaptation block. In these analyses, the within-subject factor was the performance in the early and late periods of the adaptation block (the initial 20 trials and the last 20 trials), and the between-subject factor was the cultural group (Norway vs. Japan). Second, a two-way mixed ANOVA was performed on the probability of changing explicit aim direction in the adaptation block. In this analysis, the within-subject factor was whether or not the participant was able to reach the target on the immediately preceding trial (i.e., Hit and Miss scores), and the between-subject factor was the cultural group (Norwegian vs. Japanese). By conducting this analysis, we answer whether explicit strategies are modulated by cognitive biases that differ between groups. At this regard, we hypothesized that the Japanese participants would be more susceptible changing their strategies than the Norwegians by showing more changes in their movement after they failed to reach the target than after they hit the target. According to the literature, it is expected that the actions of the Japanese group should be more strongly motivated by their failures than by their successes³⁴. Third, a two-way mixed ANOVA was performed for the aftereffects and residual aftereffects in the terminal-feedback and washout blocks, with the blocks as the within-subject factor and the cultural group as the between-subject factor. These analyses examine the difference in implicit

learning that is evaluated from movement errors. In the three ANOVAs described above, if a significant interaction was found, post hoc comparisons would be conducted using Shaffer's modified sequentially rejective Bonferroni procedure to control the familywise error rate. Fourth, correlation analysis was performed between indices reflecting implicit components (the implicit learning measure in the last period of the adaptation block, the aftereffects in the terminal-feedback and washout blocks, and the estimated learning rate of the slow process of the multi-state model³⁷). For this purpose, we calculated partial correlation coefficients between the aftereffects in the terminal-feedback and washout blocks and the implicit component that was calculated from verbal reports in the adaptation block and the learning rate of the slow process of the multi-state model³⁷.

Data availability

The datasets used and/or analyzed in the present study are available from Psych Archives. <https://psyarch.org/en/item/3a363cc8-b153-487b-9bc7-880eac89cf6e>.

Code availability

In the present study, MATLAB R2018a and R2022a were used to conduct experiments, analyze data, and create figures. The underlying code for the present study is not publicly available but may be made available to qualified researchers on reasonable request to the corresponding author.

Received: 8 July 2024; Accepted: 15 June 2025;

Published online: 02 July 2025

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Acknowledgements

This work was supported by the Japan Society for the Promotion of Science (JSPS), KAKENHI (grant numbers 20K22266 and 20H01785) and the JSPS Scholarship in Norway for FY2023.

Author contributions

Y.I. conceived the original idea. C.Y. carried out the experiment, analyzed the data, and wrote the manuscript with support from Y.I. and C.R. Y.I. and C.R. supervised the project.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s41539-025-00335-0>.

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