Divisively normalized neuronal processing of uncertain visual feedback for visuomotor learning

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Summary

When encountering a visual error during a reaching movement, the motor system improves the motor command for the subsequent trial. The degree of improvement is well-known to be degraded with visual error uncertainty, which is considered evidence that the motor system optimally estimates the error. However, it remains unclear how such statistical computation is accomplished. Here, we propose an alternative motor learning scheme implemented with a divisive normalization (DN) mechanism. This scheme assumes that when an uncertain visual error is provided by multiple cursors, the motor system processes the error conveyed by each cursor and integrates the information using DN. The DN scheme can reproduce the patterns of learning response when 1, 2, or 3 cursors are concurrently displayed and predict how the increase in the visual error uncertainty degrades the learning response. Our proposed scheme provides a novel view of how the motor learning system updates the motor command according to visual error information.

Introduction

Accurate movements are maintained across trials by the ability of the motor system to correct movement according to the difference between the actual and predicted sensory information (i.e., sensory prediction error) (Shadmehr et al., 2010). However, sensory information is not always reliable enough because of the noise inherent in the environment and the nervous system (Faisal et al., 2008). The problem of how the brain updates the motor command based on such imperfect sensory information has been investigated by manipulating the degree of uncertainty in the sensory (primarily visual) feedback for the reaching movements: the visual cursor was blurred (Burge et al., 2008) or the visual feedback was provided by a population of dots (Fig.1a) (Wei & Körding, 2010; Körding & Wolpert, 2004; Tsay et al., 2021). These previous studies consistently reported that motor adaptation was impaired when the uncertainty of visual feedback information was increased.

The impairment of motor adaptation was generally explained by the framework of statistical estimation. According to the idea of maximum likelihood estimation (MLE), the motor system optimally estimates the error by combining the observed sensory information and the sensory information predicted by the motor command through the forward model (Wolpert et al., 1995; Vaziri et al., 2006; Burge et al., 2008; Shadmehr et al., 2010; Korenberg & Ghahramani, 2002). Thus, as the uncertainty of actual sensory information increases, the motor system relies more on sensory prediction, and the resultant reduction of estimated error leads to impairment of the motor adaptation (Burge et al., 2008; Wei & Körding, 2010) (Fig.1b). Previous studies have proposed that the computation of MLE is implemented by the probabilistic population coding (Ma et al., 2006; Pouget, 2013; Ma et al., 2014) by which the activity levels (or gain) of neurons depend on the uncertainty of the sensory information. Notably, this scheme assumes the presence of uncertainty of sensory information. For example, when visual feedback is provided by a cloud of dots (Fig.1a), the uncertainty of the feedback is assumed to be encoded by the statistical dispersion of dots. However, considering that each dot should convey reliable visual error

information, such statistical encoding is not trivial. A crucial question is how the uncertainty of visual feedback could emerge from such reliable outputs from a population of dots.

In this study, we tried to take an alternative approach. We assumed that all the dots conveyed the visual error information and that the information was integrated by a divisive normalization mechanism to be used for visuomotor learning. Divisive normalization has been proposed as a canonical computational mechanism in neuronal circuits to integrate the outputs from a population of neurons—the neuronal activity is normalized by the pooled activities of neurons (Carandini & Heeger, 2011; Kouh & Poggio, 2008). This computation explains a wide range of functions regulating neural responses at an early stage of sensory coding (Heeger, 1992b; Rabinowitz et al., 2011; Olsen et al., 2010; Busse & Carandini, 2009) and higher-order processes, including attention (Reynolds & Heeger, 2009), decision making (Louie et al., 2011; Louie & Glimcher, 2012), or multisensory integration (Ohshiro et al., 2011; 2017). Our previous study (Hayashi et al., 2020) demonstrated that the motor learning response to visual and proprioceptive perturbations can be explained by divisive normalization, implying that the computation based on divisive normalization in the neuronal-circuit level could be reflected in the motor learning behavior.

The present study examined the possibility that the visuomotor learning response to uncertain visual feedback can be explained by the divisive normalization (DN) mechanism. Firstly, we introduced the visuomotor learning model based on DN mechanisms. Then, we validated the model by examining how the reaching movement direction was updated in the next trial (i.e., the aftereffect; we will call it “learning response”) after single, double, or triple cursors moving in different directions were concurrently presented (Kasuga et al., 2013). Finally, we determined whether the model could reproduce the previously reported empirical result that the leaning response decreased as the variance of a cloud of dots increased (Körding & Wolpert, 2004; Wei & Körding, 2010). Additionally, we determined whether the model could predict the recently reported result that the degree of reduction in the learning response with the variance depended on the mean size of visual error (Tsay et al., 2021).

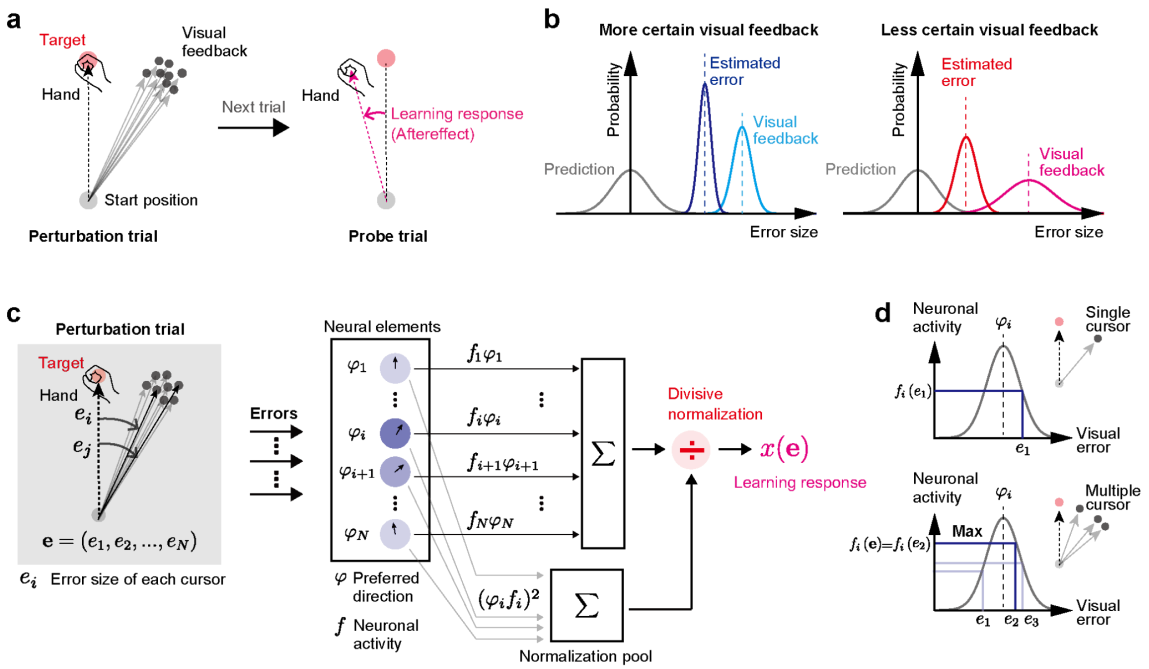

Figure 1. The divisive normalization (DN) mechanism processing visual prediction errors. **a**, In previous studies, uncertain visual feedback was provided by a population of dots. The learning response to such uncertain visual feedback can be evaluated by measuring the movement direction (i.e., the aftereffect or "learning response" herein). **b,** According to the maximum likelihood estimation scheme, the motor system estimates the error by combining the actual visual information with the visual information predicted by the motor command. The more uncertain the visual information, the smaller the estimated error, which reduces the learning response. **c,** Proposed DN model. We consider that each dot conveys different visual error information and that the information from dots is integrated by a DN mechanism to produce the learning response. **d,** In our DN model, the neuronal element encodes the visual error according to the Gaussian tuning function with the maximum operation. When multiple visual errors are concurrently provided, the activity level of the element is determined by the maximal value (lower panel).

Results

The present study considered the single-trial-adaptation experiment for reaching movements (Marko et al., 2012; Kasuga et al., 2013; Castro et al., 2014; Albert & Shadmehr, 2016; Hayashi et al., 2020) to investigate the learning response. The learning response was often quantified by the changes in reaching movement direction in the next trial after receiving visual error information (learning response in Fig.1). We first introduce the computational model and then describe the experiments used to validate the model.

DN model

To investigate the influence of visual error uncertainty information on visuomotor adaptation, previous studies have used a population of dots as a visual cursor and manipulated the degree of uncertainty by the size of the dots' distribution (Fig.1a). In those studies, the visual error information was represented by the mean and variance of the dots. The current study used a more mechanistic approach: we considered that each dot conveyed different visual error information (e_i), and the information of all dots was integrated by a DN mechanism (Carandini & Heeger, 2011) to compute the motor command in the next trial (Fig.1c).

We assumed that each neural element for visuomotor learning responds to multiple visual errors ($\mathbf{e} = (e_1, e_2, ..., e_N)$ according to the tuning function $f_j(\mathbf{e})$ (Fig.1d; receptive field of the j-th element). The outputs of all elements were integrated by a DN mechanism (Fig.1c) to determine the learning response ($x(\mathbf{e})$) as follows:

$$x(\mathbf{e}) = \frac{w\boldsymbol{f}(\mathbf{e})\boldsymbol{\varphi}^t}{[1 + k|\boldsymbol{f}(\mathbf{e}) \circ \boldsymbol{\varphi}|^2]^m}, \quad (1)$$

where w, k and m are constants (m was fixed to 1). The element of $\boldsymbol{\varphi} = (\varphi_1, \varphi_2, \ldots, \varphi_M)$ and $f(\mathbf{e}) = (f_1(\mathbf{e}), f_2(\mathbf{e}), \ldots, f_M(\mathbf{e}))$ represent, respectively, the preferred direction (M: the number of elements) and the activity level of each neuronal element, and $\circ$ is an element-wise multiplication operator (Hadamard product). We also assumed that the activity of a neuronal element is expressed as a Gaussian tuning function with the maximum operation (Kouh & Poggio, 2008):

$$f_j(\mathbf{e}) = \max_i \left[\exp\left\{-\frac{(e_i - \varphi_j)^2}{2s^2}\right\}\right], \quad (2)$$

where s is the tuning width (Fig.1d).

Experiments used to validate the DN model

We performed 3 experiments. Experiment 1 aimed to examine whether the DN model can capture the pattern of the learning response when redundant visual error information was imposed by concurrently presenting 1, 2, or 3 visual cursors (Kasuga et al., 2013). Experiments 2

and 3 aimed to examine if the model reproduced the results conventionally explained by the MLE model, i.e., the learning response decreases with the level of the uncertainty of visual error.

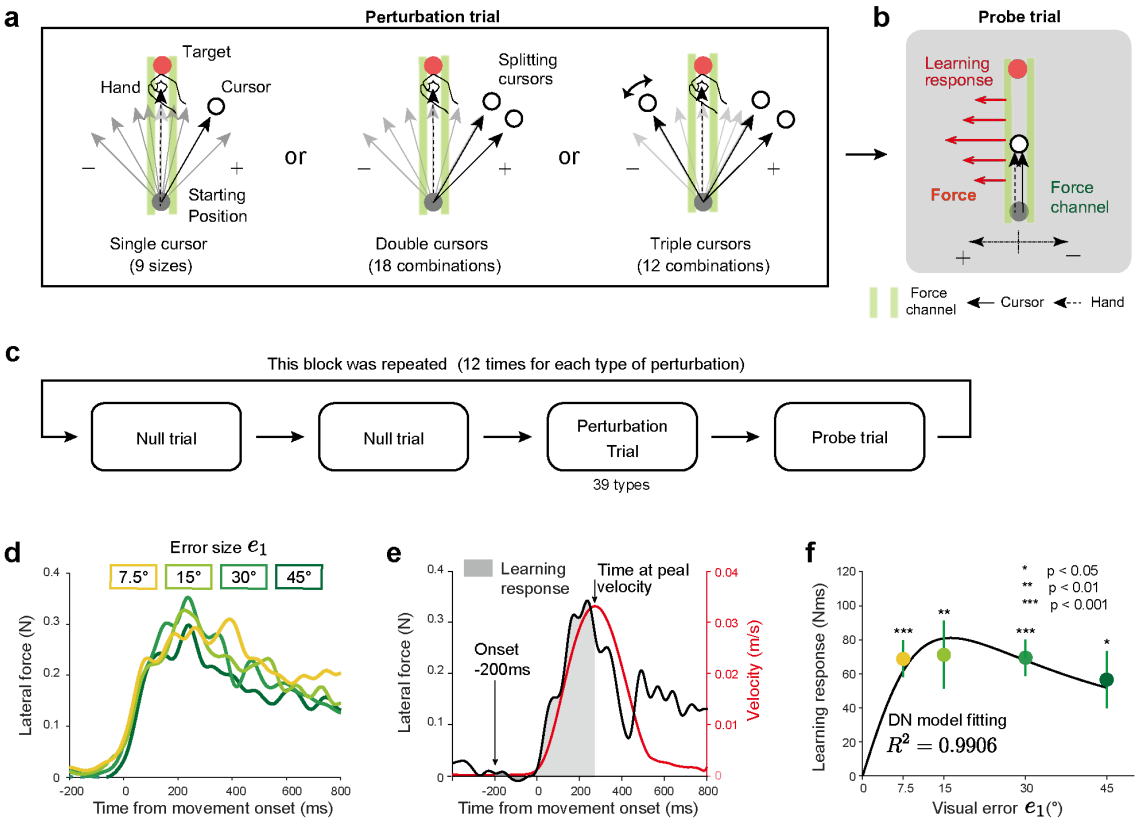

Figure 2. Procedures of experiment 1. **a, b**, Participants performed reaching movements towards a front target (distance = 10 cm). In the perturbation trials (**a**), the visual perturbation was imposed on the cursor(s). The number of cursors was 1 (left, single-cursor perturbation condition), 2 (middle, double-cursor perturbation condition), or 3 (right, triple-cursor perturbation condition). In total, there were 39 types of visual perturbations. In the perturbation trial, the hand trajectory was constrained by the force channel. In the subsequent probe trial (**b**), the learning responses were measured by the force exerted against the force channel. **c**, Participants repeated a block consisting of 2 null trials, a perturbation trial, and probe trial. **d**, The trace of lateral force exerted against the force channel in the probe trial. **e**, The learning response was evaluated as the force integrated from the force onset (200 ms before the movement onset) to the time of peak velocity (inset). **f**, The experimental result of the learning response for the single-cursor perturbation condition (green line). The error bars represent the standard error across the participants. The divisive normalization model was fitted with the learning responses (black line).

Experiment 1: Learning response to multiple visual errors

In experiment 1 (8 participants: 5 men and 3 women), we examined a single-trial visuomotor adaptation induced by visual perturbation to the cursor(s). Thirty-nine types of perturbations were used (Fig.2a). In the single-cursor perturbation condition, the visual error (e_1) was imposed

by rotating the cursor's movement direction from the target direction (e_1 = 0°, ±7.5°, ±15°, ±30°, and ±45° [9 types]). In the double-cursor perturbation condition, 2 cursors were moved concurrently in different directions. Each cursor has different visual errors (e_1 and e_2 are a combination of 0°, ±15°, ±30°, and ±45° excepting $|e_1| = |e_2|$, i.e., ${}_7C_2 - 3 = 18$ types). In the triple-cursor perturbation condition, 2 cursors' errors were fixed (e_2 = 30° and e_3 = 45°), and the error of the remaining cursor was e_1 = -45°, -30°, -15°, 0°, 15°, and 22.5° (6 types). There were also 6 symmetric patterns of perturbations in the triple-cursor perturbation condition (e_1 = 45°, 30°, 15°, 0°, -15°, and -22.5°; e_2 = -30°; and e_3 = -45°). One set of trials consisted of 4 trials: a perturbation trial (1 of 39 types was pseudo-randomly chosen) and a probe trial (Fig.2b) followed by 2 null trials to wash out the learning effect (Fig.2c).

During the perturbation and the subsequent probe trials, the hand trajectories were constrained in a straight line from the start position to the target using the force-channel method (Scheidt et al., 2000). We measured the lateral force against the force channel to measure the feedback response in the perturbation trial and the learning response in the probe trials.

Learning response to the single-cursor perturbation condition

Figure 2d illustrates the evolvement of lateral forces against the force channel during the probe trials for the single-cursor perturbation condition. The presence of the learning response was confirmed as the lateral force in the opposite direction to the visual error imposed in the perturbation trials. The learning response was quantified as the sum of lateral forces integrated over the time interval from the force onset to the time at the peak handle velocity (i.e., feedforward component; Fig.2e). Note that this measure is a proxy of the change in the movement direction normally used to quantify the learning response (Hayashi et al., 2020).

The perturbations induced significant learning responses for the single-cursor perturbation condition (Fig.2f) (e_1 = 7.5°, $t(7) = 6.354$, $p < 0.001$; e_1 = 15°, $t(7) = 3.564$, $p = 0.009$; e_1 = 30°, $t(7) = 6.504$, $p < 0.001$; e_1 = 45°, $t(7) = 3.354$, $p = 0.012$). However, there were no significant differences between the perturbation sizes ($F(3,21) = 0.783$, $p = 0.517$), indicating that the

learning response did not increase linearly with the size of perturbation but was saturated (Wei & Körding, 2009; Marko et al., 2012; Kasuga et al., 2013; Kim et al., 2018; Tsay et al., 2021; Hayashi et al., 2020). Notably, this saturation of the learning response with the error size was naturally reproduced by the DN model because of the normalization effect (Hayashi et al., 2020). Indeed, the DN model (equations 1 and 2) can be fitted well with the learning responses for the single-cursor perturbation condition (Fig.2f; $R^2 = 0.9906$, $w = 9.693\times10^3$, s = 23°, $k = 5.1885$).

Learning response to double- and triple-cursor perturbation conditions

We used the DN model identified by the learning responses of the single-cursor perturbation condition (Fig.2f) to predict the learning responses for the double- and triple-cursor perturbation conditions. The model predicted that, in the double-cursor perturbation condition, the learning responses did not increase by adding another cursor in the same directions (e_2 = 15°, 30°, and 45°) (Fig.3a). In contrast, a substantial impact was observed in the other perturbation types: the addition of another cursor moving in the target direction (e_2 = 0°) reduced the learning responses, and the addition of another cursor in the opposite direction (e_2 = -15°, -30°, and -45°) further decreased or reversed the learning responses (Fig.3a).

The empirically observed pattern of the learning response for the single- and double-cursor perturbation conditions (Fig.3b) was consistent with the model's prediction (Fig.3a). We characterized the differences among the perturbation conditions by analysing the learning responses averaged over e_1 = 15°, 30°, and 45° (the inset in Fig. 3c). The model predicted that the averaged responses were not so different between the single and e_2 = 15°, 30°, and 45° (Fig.3c). However, they were considerably reduced for e_2 = 0°, -15°, -30°, and -45° compared with the single-cursor perturbation condition (Fig.3c). The prediction was consistent with the experimental data (Fig.3d). Indeed, one-way repeated measures analysis of variance (ANOVA) indicated that the averaged learning responses significantly differed between the size of e_2 ($F(7,49) = 24.828$, $p = 4.512\times10^{-14}$); the post hoc test revealed that the learning response was not significantly changed with the addition of another cursor in the same direction (e_2 = 15°, 30°, and

45°, $p > 0.05$ by Holm correction), but it significantly decreased with the addition of cursor perturbation in the opposite direction (e_2 = -15°, -30°, and -45°, $p < 0.001$ by Holm correction) or in the 0° direction (e_2 = 0°, $p = 0.003$ by Holm correction). There were also significant differences between e_2 = 0° and e_2 = 15° ($p = 0.007$ by Holm correction), between e_2 = 0° and 30° ($p < 0.001$ by Holm correction), between e_2 = 0° and e_2 = 45° ($p = 0.011$ by Holm correction), and between e_2 = 0° and e_2 = -30°, - 45° ($p < 0.001$ by Holm correction).

Figure 3e shows the DN model prediction of how the learning responses were different between the double-cursor perturbation conditions (e_2 = 30° or e_2 = 45°) and the triple-cursor perturbation conditions (e_2 = 30° and e_3 = 45°). The model predicted that the concurrent presentation of additional 2 cursors (e_2 = 30° and e_3 = 45°) had no significant impact on the learning responses for the double-cursor perturbation conditions (Fig.3e). As predicted by the DN model, the experimental results demonstrated that the influence of the concurrent presentation of cursors (e_2 = 30° and e_3 = 45°) on the learning responses was small (Fig.3f). Two-way repeated measures ANOVA indicated that there was no significant difference between the learning responses for the double- and triple-cursor perturbation conditions (e_1 = 15°, 0°, -15°: $F(2,28) = 0.364$, $p = 0.701$).

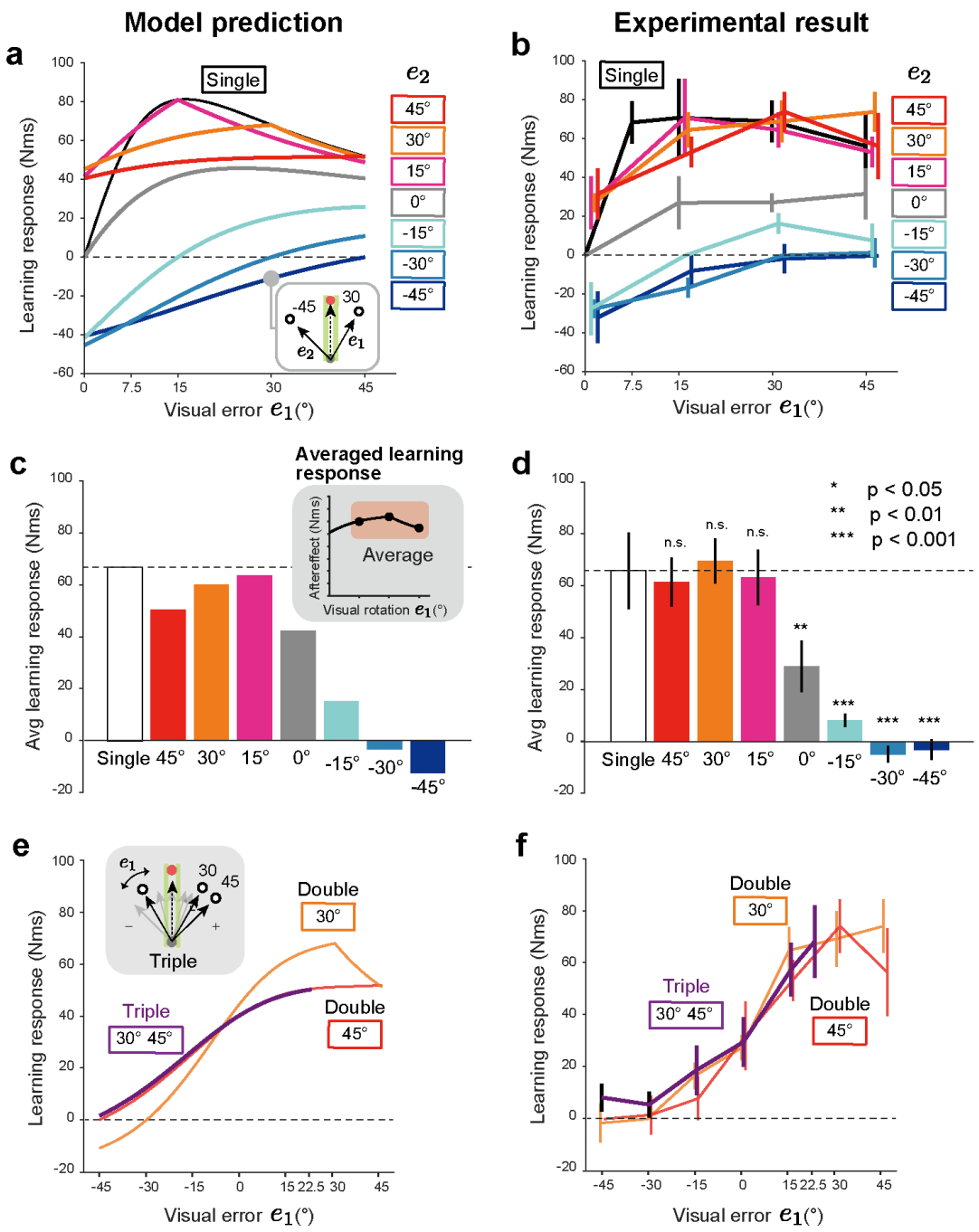

Figure 3. Learning responses for double- and triple-cursor perturbation conditions in experiment 1. **a**, The divisive normalization (DN) model prediction for the double-cursor perturbation condition. The parameters of the DN model (equations 1 and 2) were identified by fitting the learning responses for single perturbations (**Fig.2f**). The learning response for the single-cursor perturbation condition is also displayed (black line). **b,** The experimentally observed learning responses of the double-cursor perturbation condition. **c,** The influence of an additional cursor (e_2) on the learning response was evaluated as the averaged learning response for e_1 =15°, 30°, 45° (inset). **d,** The experimental results of the averaged learning response in the double-cursor perturbation condition. **e,** The DN model prediction for the triple-cursor perturbation condition compared with that for the double-cursor perturbation condition. **f,** The experimentally observed learning responses for the triple-cursor perturbation condition. The error bars represent the standard error across the participants.

Can the MLE model explain the pattern of learning responses?

A natural question is if the previously proposed MLE can explain the learning responses of the double- and triple-cursor perturbation conditions. According to the MLE framework, the motor system estimates the error by integrating the observed visual cursor information (observed error) with the information predicted by the motor command (predicted error) (Fig.1b). Assuming that the uncertainty of both information is represented by a normal distribution, the optimally estimated learning response $x(e)$ to the observed visual error e should be

$$x(e) = c\frac{\sigma_p^2}{\sigma_p^2 + \sigma^2(e)}e, \quad (3)$$

where σ_p^2 is the variance of predicted error, $\sigma^2(e)$ is the variance of observed error, and c is a constant. We assumed that $\sigma^2(e)$ depends on the size of e; otherwise, the nonlinear learning response to e (Fig.2f) cannot be reproduced. We also made a natural assumption that the mean value for the predicted and observed error are 0 and e, respectively. Considering the previous studies suggesting that the standard deviation of the signals linearly increases with the mean signal intensity (Jones et al., 2002; Goris et al., 2014), the standard deviation $\sigma(e)$ can be represented as follows:

$$\sigma(e) = \sigma_v + k_v |e|, \quad (4)$$

where σ_v is the standard deviation of visual error when the error is 0, and k_v is a constant.

If the same estimation based on the MLE holds for the multiple cursor condition (when the number of cursor is N), the learning response can be expressed as follows:

$$x(\mathbf{e}) = c\left(\frac{1}{\sigma_p^2} + \sum_{i=1}^{N}\frac{1}{\sigma^2(e_i)}\right)^{-1}\left(\sum_{i=1}^{N}\frac{e_i}{\sigma^2(e_i)}\right), \quad (5)$$

As in the DN model, we obtained the σ_p^2 and $\sigma^2(e)$ by fitting the learning response for the single-cursor perturbation condition with equations 3 and 4, and then predicted the learning responses for double- and triple-cursor perturbation conditions with equation 5.

Equations 3 and 4 could reasonably fit the learning responses for the single cursor

condition (Fig.4a; $R^2 = 0.9983$, $c = 2.963 \times 10^5$, $\sigma_v/\sigma_p = 122.2$, $k_v/\sigma_p = 8.055$). The identified MLE model predicted that the learning responses increased and decreased, respectively, with the additional perturbation to the same direction (e_2 = 15°, 30°, 45°) and to the opposite direction (e_2 = -15°, -30°, -45°) (Fig.4b). The MLE model also predicted that the learning responses for the triple-cursor perturbation condition exhibited a peculiar modulation pattern with the size of e_1 (Fig.4c). However, the experimental results (Fig.3b, f) were inconsistent with these MLE model's predictions.

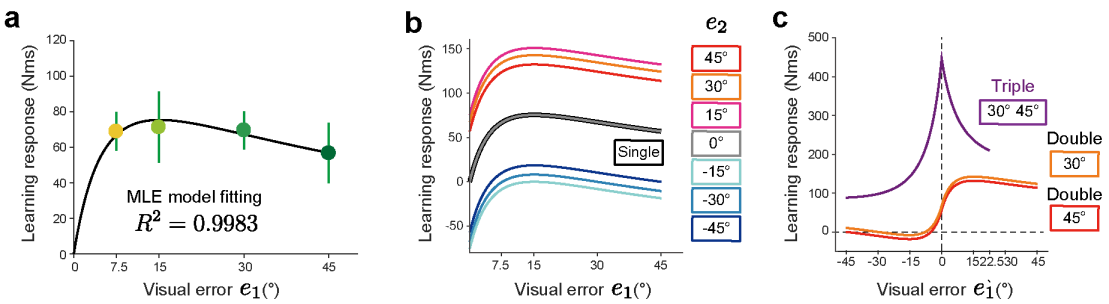

Figure 4. The result of model fitting and prediction by the maximum likelihood estimation (MLE) model. **a,** The modified MLE model (equations 3–5) could reproduce the learning responses for the single-cursor perturbation condition. **b–c,** The MLE whose parameters obtained by the learning responses for the single-cursor perturbation condition was used to predict the earning responses for double- (**b**) and triple-cursor perturbation conditions (**c**). However, these predictions were totally different from the experimental results (**Fig.3b,f**).

Experiment 2: Learning response to uncertain visual feedback

Since the double- and triple-cursor perturbation conditions were peculiar from the ecological viewpoint (a cursor split into 2 or 3 pieces), it is still possible that only the MLE model can explain the learning responses for a more realistic case like when the visual error information is provided by a cloud of dots (Körding & Wolpert, 2004; Wei & Körding, 2010; Burge et al., 2008; Tsay et al., 2021). We performed experiment 2 (16 participants: 11 men and 5 women) and experiment 3 (12 participants: 8 men and 4 women) to examine whether the DN model could explain the learning responses when visual feedback (cursors) was provided by a population of cursors.

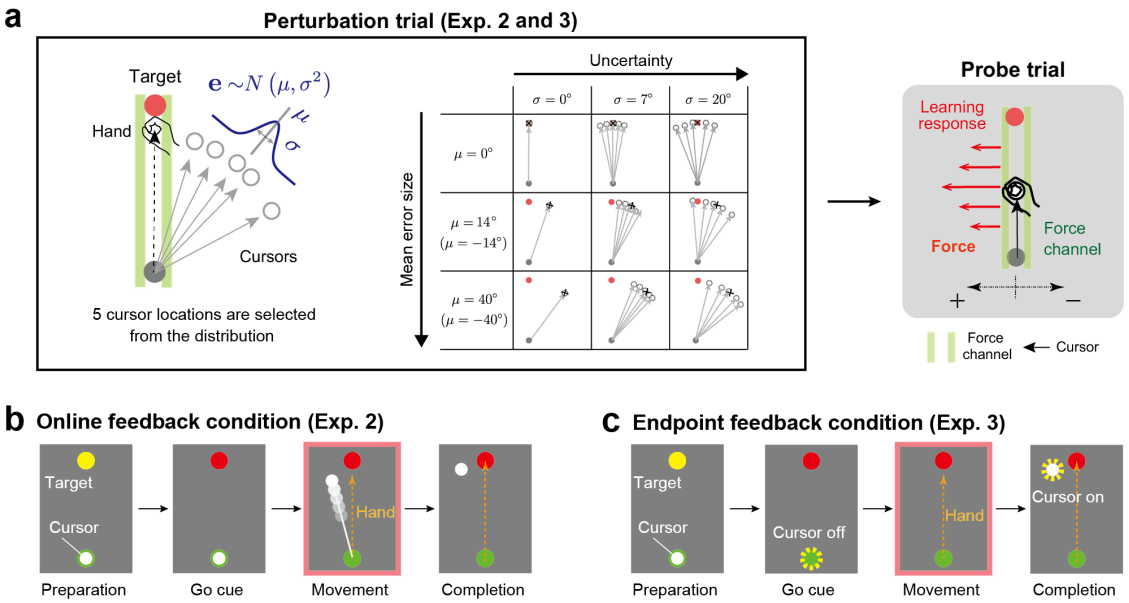

Figure 5. Experimental procedures of experiments 2 and 3. **a,** Participants performed a reaching movement towards a frontal target (movement distance = 15 cm). Five cursors were concurrently displayed as visual feedback in the perturbation trial. The directions of the cursors followed 1 of 15 types of normal distribution $N(\mu, \sigma^2)$ (μ = 0°, ±14°, ±40°; σ = 0°, 7°, 20°). The learning responses were evaluated by the lateral force against the force channel in the next probe trial. **b,** In experiment 2 (online feedback condition), the cursors were always visible during the movement. **c,** In experiment 3 (endpoint feedback condition), the cursors were visible only after termination of the movement.

As was in experiment 1, the participants repeated the experimental set consisting of a perturbation trial, a probe trial, and 2 null trials. In the perturbation trials, 5 cursors were concurrently displayed (Fig.5a). In every perturbation trial, the angles of cursors' movement direction were randomly drawn from 1 of 15 different normal distributions ($N(\mu, \sigma^2)$; μ = 0°, ±14°, ±40°; σ = 0°, 7°, 20°) (Fig.5a). The cursor was visible throughout the movement in experiment 2 (Fig.5b), whereas the cursor was only visible after completion of the reaching movement in experiment 3 (Fig.5c).

First, we predicted the learning responses for these uncertain visual error conditions by the DN model (equations 1 and 2) whose parameters were identified by fitting the learning responses for the single-cursor perturbation condition (i.e., σ = 0°) in experiment 2 (Fig.6a). As was shown in the results in experiment 1, the fitted DN model captured the modulation of the learning responses with the error size (Fig.6a; w = 0.2722, s = 26°, k = 5.444×10^{-5}). This identified DN

model was used to predict the pattern of the learning responses when uncertainty was introduced to the visual error information (Fig.6b). When the visual error size was small (μ = 14°), the increase in uncertainty decreased the learning responses (Fig.6b), which was consistent with the prediction of the conventional MLE model (Burge et al., 2008; Wei & Körding, 2010). Additionally, as Tsay et al. (2021) have recently reported, when the visual error size was large (μ = 40°), the amount of decrement of the learning responses was suppressed (Fig.6b). Notably, the MLE model predicted that the decrement ratio of the learning responses with the variance should be the same irrespective of the mean value, resulting in greater reduction of learning response for μ = 40° (the red broken line in Fig.6b).

The observed learning responses in experiment 2 were similar to the pattern predicted by the DN model (Fig.6c). Two-way repeated measures ANOVA indicated a significant interaction in the learning response between μ = 14° and μ = 40° ($F(2,28) = 8.034$, $p = 0.002$). There was a significant simple main effect for μ = 14° between σ = 0° and σ = 7°, σ = 0°, and σ = 20°, and between σ = 7° and σ = 20° ($p = 0.032$, $p < 0.001$, and $p=0.004$, respectively, by Holm correction). The learning response for σ = 7° decreased by 24.82 ± 8.49% and that for σ = 20° decreased by 53.47 ± 7.44% compared with that for σ = 0°. In contrast, when μ = 40°, there was a significant simple main effect only between σ = 7° and σ = 20° ($p = 0.046$ by Holm correction). The learning response for σ = 20° decreased by 7.09 ± 17.52% and that for σ = 7° increased by 9.88 ± 13.72% compared with that for σ = 0°. These characteristics were also evident for the temporal change of the lateral force against the force channel (Fig.6d).

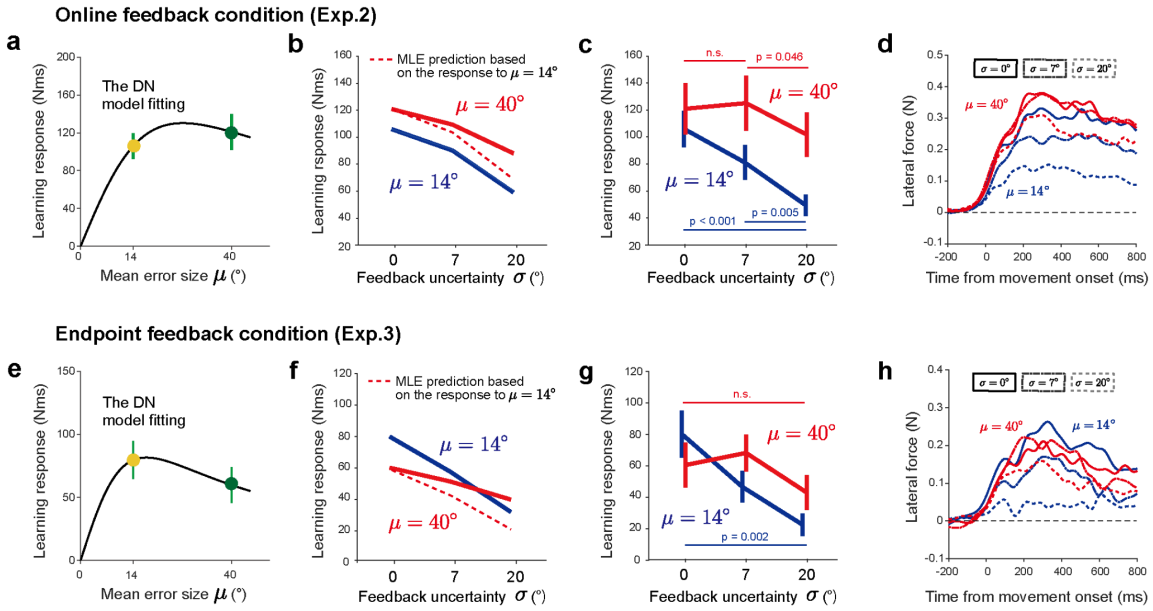

Figure 6. The divisive normalization (DN) model predictions and experimental results of experiments 2 and 3. **a,** The experimentally observed learning responses for no uncertainty conditions in experiment 2 (gray line) and the DN model fitting (red line). **b,** The DN model, whose parameter was obtained by fitting the learning responses for no uncertainty conditions in experiment. 2 (**a**), was used to predict the change of the learning response to visual uncertainty when the mean error size is small (μ = 14°, blue line) and large (μ = 40°, red line). The MLE model predicted that the decrement ratio of learning response with the variance was independent of the mean error size. The broken red line was obtained when the decrement ratio of learning response for μ = 40° was same as that for μ = 14°. **c,** The experimentally observed learning responses in experiment 2 are consistent with the DN model prediction (**b**). **d,** The lateral force traces in the probe trial. **e–h,** The DN model fitting for no uncertainty conditions (**e**), DN model prediction (**f**), experimental result (**g**), and time series of the lateral force (**h**) in experiment 3 (endpoint feedback conditions). The error bars represent the standard error across the participants.

Experiment 3 examined the case in which the visual feedback was visible only after the movement ended (Fig.5c). The endpoint feedback has been more commonly used in previous studies than the online feedback (Wei & Körding, 2010; Burge et al., 2008; Tsay et al., 2021). Figure 6e–h demonstrates that similar results were obtained in the endpoint feedback condition. Two-way repeated measures ANOVA indicated the presence of a significant interaction in the learning response between μ = 14° and μ = 40° ($F(2,18) = 3.822$, $p = 0.041$). There was a significant simple main effect for μ = 14° between σ = 0° and σ = 20° ($p = 0.002$ by Holm correction). In contrast, there was no significant simple main effect for μ = 40° ($F(2, 18) = 2.471$, $p = 0.113$). The DN model, whose parameters were obtained by fitting the learning responses for the single-cursor perturbation condition (Fig.6e; i.e., σ = 0°) in experiment 3 (Fig.6f; $w = 2.720$, s = 24°, $k = 0.0013$), could capture the learning response modulation for the endpoint feedback

condition (Fig.6g). These characteristics were also evident for the temporal change of the lateral force against the force channel (Fig.6h).

Pattern of the feedback responses

In experiments 1 and 2, the visual error information was visible throughout the movement, which induced feedback responses in the perturbation trial. Considering that a feedback response in the perturbation trial could serve as a teaching signal for the learning response in the subsequent trial (Kawato et al., 1987; Albert & Shadmehr, 2016), the pattern of learning responses explained by the DN model could already be seen in the pattern of the feedback responses. We examined this possibility by quantifying online feedback responses as the integrated lateral force over the time interval to the time at the peak hand velocity for 100 ms (Fig.7a).

Figure 7a illustrates how the feedback responses induced by a single visual perturbation in the perturbation trials of experiment 1 depended on the visual error size. As compared with the learning responses (Fig.2f), the linearity of feedback response modulated with the size of the error was greater. We fit the data with the DN model (equations 1 and 2) for the single-cursor perturbation condition and obtained the parameters (Fig.7a; $R^2 = 0.9961$, $w = 0.0117$, $s = 23°$, $k = 4.7345\times10^{-6}$). The greater linearly was reflected in the smaller value of k (cf. $k = 5.1885$ in experiment 1). Using the identified DN model, we predicted the feedback responses for the double- (Fig.7b) and triple-cursor perturbation conditions (Fig.7c). The predicted pattern was consistent with the experimentally observed feedback responses (Fig.7b, c). Moreover, the DN model, fitted with the online responses for the 0 conditions in experiment 2 ($w = 0.0646$, $s = 30°$, $k = 1.9635 \times 10^{-5}$), could reproduce the modulation pattern of the online responses induced by uncertain visual cursors (Fig.7d). These results suggested that the divisive normalization pattern could also explain the modulation pattern of the online feedback response, but the nonlinearity was weaker for the feedback response than for the learning response.

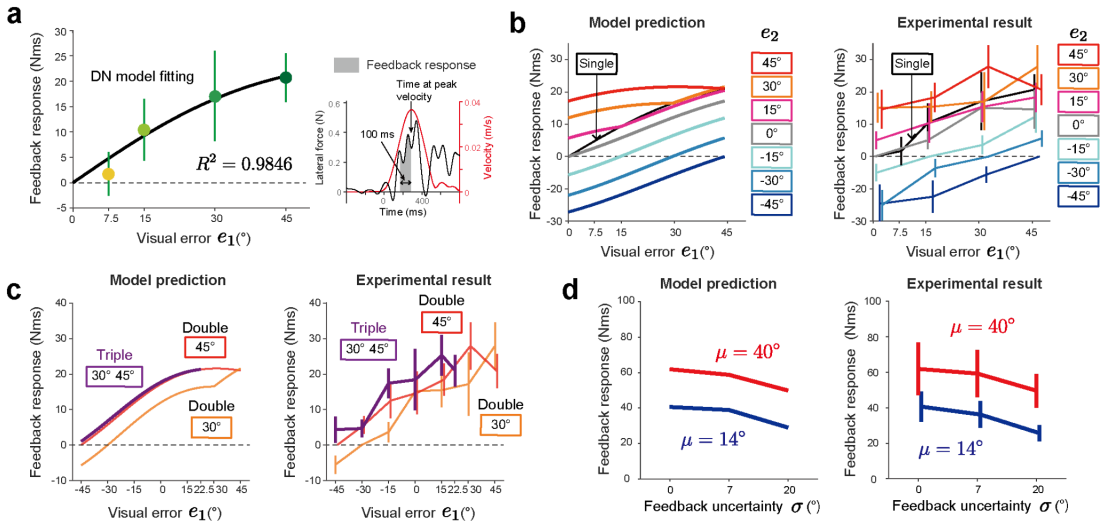

Figure 7. The pattern of the feedback response. **a,** The experimental result of the feedback responses for the single-cursor perturbation condition in experiment 1. The feedback response was quantified by the force impulse from T-100 to T (T: the timing at the peak velocity) (right panel). The DN model can be fitted well with these feedback responses (left panel). **b,** The DN model, fitted by the feedback responses for single perturbations, to predict the feedback responses for double perturbations (left panel). The experimentally observed feedback responses are consistent with the DN model prediction (right panel). **c,** The DN model prediction (left panel) and experimental result of the feedback responses for triple perturbations (right panel). **d,** The DN model, whose parameter was obtained by fitting the feedback responses for no uncertainty conditions in experiment. 2, to predict the change of the learning response to visual uncertainty (left panel), and the experimentally observed feedback responses in experiment 2 (right pane).

Discussion

The motor system maintains accurate movements by constantly updating the motor command according to the movement error. A significant problem is how the motor system estimates movement error in the presence of noise and uncertainty in environments and the central nervous system. Previous studies have proposed the idea that the motor system optimally estimates the error by integrating the actual sensory information and the sensory information predicted by the motor command. This optimal estimation scheme can clearly explain the well-known phenomenon that the learning response (i.e., the aftereffect) is reduced as the uncertainty of visual error feedback increases (Burge et al., 2008; Wei & Körding, 2010).

In contrast to the conventional idea, the present study has proposed a more mechanistic computational scheme. Crucially, we assume that the uncertain visual error information is processed by a DN mechanism (Carandini & Heeger, 2011). The proposed DN model (equations

1 and 2) captured the complicated learning response modulation pattern when the visual error information is provided by a single, double, or triple cursor (Fig.3). Furthermore, the DN model could reproduce the previous results that the learning response decreases with the level of uncertainty of visual feedback (Fig.6) without assuming that the uncertainty of visual error information is represented by the mean and variance of the cursors' locations. These results demonstrated that the DN mechanisms contribute to the processing of uncertain and/or redundant visual feedback information in the visuomotor learning system.

The DN model naturally reproduces the saturation of the learning response to visual error size

The optimal estimation (or MLE) model predicts that the learning response should decrease as the uncertainty of visual error information increases (equation 3). However, this model implies that the learning response linearly increases with the visual error size. Thus, additional mechanisms need to be introduced to explain the saturation of the leaning response to the large error (Wei & Körding, 2009; Marko et al., 2012; Kasuga et al., 2013, Tsay et al., 2021, Hayashi et al., 2020) (Fig.2f). Marko et al. (2012) assumed that the reduction of the learning response to the larger visual error size reflects the inherent neuronal response in the cerebellum (Soetedjo et al., 2008). Wei & Körding (2009) proposed that the motor system evaluates the relevance of visual error according to the dissociation between the visual and proprioceptive information. When there is a greater dissociation (i.e., smaller relevance), the motor system relies less on the visual error, leading to the reduction of the learning response. The present study also explored another possibility of the MLE model by considering that the uncertainty of visual error information increases with the visual error size (i.e., signal-dependent noise (Harris & Wolpert, 1998; Jones et al., 2002; Goris et al., 2014) (equation 4). In contrast to these ideas, the DN model can naturally reproduce the saturation effect owing to the normalization effect (i.e., the denominator of equation 1) without introducing additional mechanisms. Moreover, as discussed in the next section, the aforementioned optimal estimation schemes described cannot reproduce

the learning response patterns in the double- and triple-cursor perturbation conditions.

The DN model can predict the learning response to double- and triple-cursor perturbation conditions

DN provides a mechanism for processing multiple visual feedback information without presuming the statistical property of visual feedback. We tried to validate the mechanism by examining the learning responses in the simplest case in which 2 visual cursors were concurrently provided. The DN model identified by the data of the single-cursor perturbation condition (Fig.2f) predicted several characteristic patterns (Fig.3a). When a cursor moving in a direction is accompanied by another cursor moving in the opposite direction or in the 0° direction, the learning response should be reduced. In contrast, when another cursor moves in the same direction, the learning responses are largely unaffected. These predictions were consistent with the experimental result (Fig.3b). This "sub-additivity" is a hallmark of the integration of sensory information by divisive normalization (Oshiro et al., 2011; 2017). We also demonstrated that the experimentally observed patterns are similar to the predicted pattern for the triple-cursor perturbation condition (Fig.3e, f).

In contrast, according to the idea of the MLE model, the visual error information provided by multiple cursors is optimally integrated under the assumption that the visual information of each cursor has uncertainty. We modified the MLE model by including the signal-dependent noise property (equation 6), which is necessary to reproduce the saturation of the learning response in the single-cursor perturbation condition. After fitting the data with the modified MLE model (equation 5; Fig.4a), we predicted the learning responses for double- and triple-cursor perturbation conditions (Fig.4b,c). The MLE model predicted that the additional cursor changed the learning responses according to the size of additional error (Fig.4b). The MLE model also predicted that the learning response for the triple-cursor perturbation condition was considerably greater than that for the double-cursor perturbation condition (Fig.4c).

However, changes in the learning response by additional cursor(s) were not observed (Fig.3b and f). These inconsistencies between the prediction and experimental results suggest that the MLE is unlikely to be a general mechanism to compute the learning response based on the visual error information.

Learning response to uncertain visual error

A crucial problem is whether the DN model can reproduce the well-known phenomenon that the learning response decreases with the level of visual error uncertainty, which was previously explained by the MLE model (Wei & Körding, 2010; Burge et al., 2008). Using the DN model, we predicted the learning responses when 5 dots whose movement directions were sampled from normal distribution were concurrently displayed. The DN model predicted the decrease in the learning response with the variance when the mean error size was small (μ = 14°) (Fig.6b, f), and the experimental results validated this prediction (Fig.6c, g). Notably, in the DN model's framework, the motor system does not require any a priori information on the mean and variance of the population of dots. It merely encodes the error information conveyed by individual dots and integrates the information. Thus, the DN model provides a mechanistic framework to perform computations similar to the optimal estimation.

Importantly, the DN model provided an additional prediction when the mean size was large (μ = 40°). According to the MLE model, the level of reduction of the learning responses did not depend on the mean size. Yet, the DN model predicted that the level of reduction was smaller for the larger mean size (Fig.6b, f). Indeed, the experimental results supported the prediction by the DN model (Fig.6c, g). Recently, a similar result was reported (Tsay et al., 2021); the authors tried to explain the result by assuming that the distribution of dots is truncated below a certain threshold due to the inherent saturation property of the learning response (i.e., the learning response remains almost unchanged to the error beyond the threshold level). However, it should be noted that their scheme was also based on the MLE model combined with the saturation effect. The DN model is superior in that it can explain the saturation effect and the integration of

multiple error information in a unified framework.

Influence of online and endpoint feedback

In experiments 1 and 2, the visual cursor was visible throughout the movements in the perturbation trials. Although we instructed the participants not to respond explicitly to the visual error, the visual error implicitly elicits the feedback response (Day et al., 2000; Franklin and Wolpert, 2008). According to the feedback error learning hypothesis (Kawato et al., 1987), the feedback motor command is used as a teaching signal for the motor command in the subsequent trial. Indeed, a previous study demonstrated that the learning response in the probe trial is similar to the feedback response in the perturbation trial (Albert & Shadmehr, 2016).

The experimental result demonstrated that the DN property in the learning response was unlikely to be derived from the DN property in the feedback response. First, the response patterns were considerably different between the learning response and the feedback response: the feedback response pattern exhibited greater linearity as reflected by the smaller k value (i.e., the normalization effect was weaker) (Fig.3 versus Fig.7). Thus, even if the learning response is produced by the feedback response as proposed by the feedback error learning hypothesis, the DN mechanism could contribute in the neuronal processes transforming the feedback response to the learning response. Second, even when the feedback response was absent (i.e., the endpoint feedback condition [experiment 3]), the learning response still demonstrated the DN property (Fig.6e–h), clearly demonstrating that the DN property in the learning response could be generated independently of the feedback response. Further studies are necessary to clarify how the motor system uses the online and endpoint visual errors to generate the learning response and how the interaction causes the DN property in the learning response.

Neural correlates of the DN mechanism

The present study firstly demonstrated that the DN mechanism accounts for the motor adaptation to redundant and/or uncertain visual information. Do these behavioral results reflect the way of

neuronal processing for visuomotor adaptation? Alvarado et al. (2007) recorded the activity of neurons in the superior colliculus responding to visual (unisensory neurons) or both visual and auditory information (multisensory neurons). When 2 visual stimuli are provided concurrently, the authors found that the responses for >60% of neurons are smaller than the summation of responses evoked by individual visual stimulus. Such a sub-additive response is one of the signatures of the DN integration mechanism (Carandini & Heeger, 2011; Ohshiro et al., 2011; 2017). Several other studies have also reported that the DN mechanism successfully accounts for the response of V1 neurons to multiple visual stimuli (Busse et al., 2009; Carandini et al., 1997; Sato, 2016). Thus, the DN mechanism is ubiquitous for the neuronal processing of visual information. To our knowledge, no previous studies have investigated if the neurons in the cerebellum, which is responsible for motor learning, have a similar integration mechanism. However, the complex spikes of the Purkinje cell, which is thought to encode the error signal (Kitazawa et al., 1998), did not increase with the visual error size but decreased as the visual error size became greater (Soetejo et al., 2008; Marko et al., 2012). Such a nonlinear response could reflect that the activity of Purkinje cells also follows the DN mechanism, which needs to be confirmed in future studies.

In summary, we demonstrated the possibility that the visuomotor learning system processes visual error information by a divisive normalization mechanism. Differently from the conventionally proposed optimal estimation mechanism, the DN mechanism does not assume the statistical property of the uncertainty in the visual feedback (the distribution of cursors). Instead, the DN mechanism assumes that the visual error information conveyed by each cursor is integrated to determine the learning response. This mechanism was able to explain the learning responses when 1, 2, or 3 cursors were concurrently displayed. Furthermore, it reproduced the well-known phenomenon that the learning response decreased with the level of uncertainty in the visual feedback. Considering the explanatory power, the proposed idea provides a novel view of how the motor learning system updates the motor command according to the visual error information.

Materials and Methods

General experimental procedures

Thirty-six right-handed participants (24 men and 12 women aged 20–35 years) volunteered for the 3 experiments. Before the experiments started, we explained the experimental procedures, and written informed consent was obtained from all participants. The Office for Life Science Research Ethics and Safety of the University of Tokyo approved the experiments.

The participants performed reaching movements with their right hand holding the handle of a manipulandum (KINARM End-point Lab, Kinarm, Kingston, Canada). A horizontal screen was set above the handle to display a start position and a target (5 mm in diameter), and a white cursor (experiments 1 and 2: 5 mm in diameter, experiment 3: 2.5 mm in diameter) indicating the handle position. This screen prevented the participants from directly seeing their arm and handle. To reduce unnecessary movement, the wrist joint was constrained by a brace and the participants' bodies were fixed to a chair by belts.

The green target was displayed at a certain distance (experiment 1: 10 cm; experiments 2 and 3: 15 cm) away from the start position in the straight-ahead direction. A few seconds after the participants held the handle into the start position, the target color turned to magenta, which signaled "go." The participants were asked to move the handle of the KINARM robot toward the target as smoothly and as straight as possible and not to use any explicit strategy even when the cursor was perturbed. The cursor was always visible in experiments 1 and 2, whereas the cursor was visible only after completion of the reaching movement in experiment 3. To maintain a constant velocity across the trials, the warning message ("fast" or "slow") appeared at the end of each trial when the peak velocity of the handle was too fast (>450 mm/s) or too slow (<250 mm/s). The participants maintained the handle at the end position until the robot automatically returned the handle to the start position (~1.5 seconds). Before each experiment, the participants practiced 50 standard reaching movements to achieve stable movements at the appropriate

distance and in the range of appropriate velocities.

Experiment 1: Influence of presenting multiple cursors

In experiment 1 (8 participants: 5 men and 3 women), we examined a single-trial visuomotor adaptation induced by visual perturbation to the cursor(s). Thirty-nine types of perturbations were used (Fig.2a). In the single-cursor perturbation condition, the visual error (e_1) was imposed by rotating the cursor's movement direction from the target direction (e_1 = 0°, ±7.5°, ±15°, ±30°, and ±45° [9 types]). In the double-cursor perturbation condition, 2 different cursors were moved synchronously in different directions. Each cursor has different visual errors (e_1 and e_2 are a combination of 0°, ±15°, ±30°, and ±45° excepting $|e_1| = |e_2|$ i.e., ${}_7C_2$ - 3 = 18 types). In the triple-cursor perturbation condition, 2 cursors' errors were fixed (e_2 = 30° and e_3 = 45°) and the error of the remaining cursor was e_1 = -45°, -30°, -15°, 0°, 15°, and 22.5° (6 types). There were also 6 symmetric patterns of perturbations in the triple-cursor perturbation condition (e_1 = 45°, 30°, 15°, 0°, -15°, and -22.5°; e_2 = -30°; e_3 = -45°).

During the perturbation and the subsequent probe trials, the hand trajectories were constrained along the straight line between the start position and the target by using the force channel (Scheidt et al., 2000) implemented by a virtual spring (6000 N/m) and dumper (100 N/(m/s)). This procedure, combining multiple visual rotations and the force channel, enabled us to completely control the size of the visual error without introducing the proprioceptive error (Fig.2a). In the subsequent probe trials, the lateral force against the force channel was measured to evaluate the learning response (Fig.2b). One set of trials consisted of 4 trials (Fig.2c): a perturbation trial (1 of 39 perturbation types was pseudo-randomly chosen), probe trial , and 2 null trials without the force channel to wash out the adaptation effects.

Experiments 2 and 3: Influence of visual error uncertainty

Experiment 2 (16 participants: 11 men and 5 women) and experiment 3 (12 participants: 8 men

and 4 women) were performed to verify whether our DN model could predict the effect of visual feedback uncertainty (a population of cursors) on the learning responses. As was in experiment 1, the participants repeated the experimental set consisting of a perturbation trial, probe trial, and 2 null trials. In the perturbation trials, 5 cursors were concurrently displayed (Fig.5a). In every perturbation trial, the angles of cursors' movement direction were randomly drawn from 1 of 15 normal distributions ($N(\mu, \sigma^2)$; μ = 0°, ±14°, ±40°; σ = 0°, 7°, 20°) (Fig.5a). The cursor was always visible (Fig.5b) in experiment 2, whereas the cursor was only visible after completion of the reaching movement (Fig.5c) in experiment 3. Three participants were excluded from the analysis because the learning responses were not clearly observed in the single-cursor perturbation condition (1 participant and 2 participants for experiments 2 and 3, respectively).

Data analysis

The position and force data of the handle were sampled at a rate of 1000 Hz and filtered by the 4th-order zero-lag Butterworth filter with a cut-off frequency of 10 Hz. The velocity of the handle was obtained by numerically differentiating the position of the handle. The movement onset was determined as the time when the handle velocity reached 5% of the peak velocity. We quantified the learning response in the probe trials as the lateral force impulse (the summation of lateral force over the time interval from the movement onset – 200ms to the time at the peak handle velocity) (Fig.2e). We also quantified the feedback response in the perturbation trials as the sum of the lateral force over the time interval from the time at the peak velocity – 100 ms to the time at the peak handle velocity (Fig.7a). We integrated the lateral force up to the time at the peak velocity, because we focussed on only the implicit component of both responses.

In experiment 1, we collapsed the data of the lateral forces to the perturbations $\pm e_1$ in the single perturbation condition. We also collapsed the data for (e_1, e_2) and ($-e_1$, $-e_2$) (e.g., (15°, -30°) and (-15°, 30°)) in the double-cursor perturbation condition and the lateral force data for (e_1, 30°, 45°) and ($-e_1$, -30°, -45°) in the triple-cursor perturbation condition. In experiments 2

and 3, we collapsed the data of the lateral forces to the perturbation $\pm\mu$ for each of σ^2.

Model validation and prediction

To examine the validity of the DN model, we firstly fit the learning response data of the single cursor condition (experiment 1) with the DN model (equations 1 and 2). Then, using the identified parameters, we predicted the possible pattern of learning responses for the double- and triple-cursor perturbation conditions (experiment 1). We also fitted the learning responses of the conditions with $\sigma = 0°$ in experiment 2 or 3 by the DN model, and then used the identified DN model to predict how the learning responses were influenced when 5 cursors were concurrently presented. To examine whether the DN model could also capture the modulation pattern of the online feedback response, we followed the same procedure with the feedback responses in experiments 1 and 2 (Note that the feedback response was not induced in experiment 3, because the cursor was not visible during the movement.).

Previous studies have proposed an MLE model to explain the effect of visual information uncertainty on the magnitude of the learning response (equation 3). The standard MLE model, however, cannot explain the saturation of learning responses with the visual error size. To reproduce the saturation effect, we assumed that the visual error signal has the characteristic of signal-dependent noise (equation 4): the standard deviation of the visual error linearly increases with the visual error size (Jones et al., 2002; Goris et al., 2014; refer to Wei & Körding 2009 for another approach). We fit the learning responses of the single-cursor perturbation condition (experiment 1) with the MLE model and identified the parameters (equations 3 and 4). Then, we predicted the possible pattern of learning responses for the double- and triple-cursor perturbation conditions using equation 5.

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Author contributions

Conceptualization, Methodology, Formal Analysis, and Writing: Y.M., T.H., and D.N.; Investigation, Y.M.; Supervision, D.N.

Declaration of Interest

The authors declare no competing interests.

References

Albert, S.T., and Shadmehr, R. (2016). The neural feedback response to error as a teaching signal for the motor learning system. J. Neurosci. *36*, 4832–4845.

Alvarado, J.C., Vaughan, J.W., Stanford, T.R., and Stein, B.E. (2007). Multisensory versus unisensory integration: contrasting modes in the superior colliculus. J. Neurophysiol. *97*, 3193–3205.

Beck, J.M., Latham, P.E., and Pouget, A. (2011). Marginalization in neural circuits with divisive normalization. J. Neurosci. *31*, 15310-15319.

Burge, J., Ernst, M.O., and Banks, M.S. (2008). The statistical determinants of adaptation rate in human reaching. J. Vis. *8*, 1–19.

Busse, L., Wade, A.R. & Carandini, M. (2009). Representation of concurrent stimuli by population activity in visual cortex. Neuron *64*, 931–942.

Carandini, M., and Heeger, D.J. (2011). Normalization as a canonical neural computation. Nat. Rev. Neurosci. *13*, 51–6

Carandini, M., Heeger, D.J., and Movshon, J.A. (1997). Linearity and normalization in simple cells of the macaque primary visual cortex. J. Neurosci.*17*, 8621–8644.

Castro L.N.G., Hadjiosif A.M., Hemphill, M.A., and Smith, M.A. (2014). Environmental Consistency Determines the Rate of Motor Adaptation. Current Biology. *24*, 1050–1061.

Day, B.L., and Lyon, I.N. (2000). Voluntary modification of automatic arm movements evoked by motion of a visual target. Exp. Brain Res. *130*, 159-168.

Faisal, A.A., Selen, L.P.J., and Wolpert, D.M. (2008). Noise in the nervous system. Nat. Rev. Neurosci. *9*, 292–303.

Franklin, D.W., and Wolper, D.M. (2008). Specificity of reflex adaptation for task-relevant variability. J. Neurosci. *28*, 14165-14175.

Goris, R.L., Movshon, J.A., and Simoncelli, E.P. (2014). Partitioning neuronal variability. Nat. Neurosci. *17*, 858–865.

Harris, C.M., and Wolpert, D.M. (1998). Signal-dependent noise determines motor planning. Nature *394*, 780–784.

Hayashi, T., Kato, Y., and Nozaki, D. (2020). Divisively normalized integration of multisensory error information develops motor memories specific to vision and proprioception. J. Neurosci. *40*, 1560–1570.

Heeger, D.J. (1992a). Half-squaring in responses of cat striate cells. Vis. Neurosci. *9*, 427–443.

Heeger, D.J. (1992b). Normalization of cell responses in cat striate cortex. Vis. Neurosci. *9*, 181–197.

Jones, K.E., Hamilton, A.F., and Wolpert, D.M. (2002). Sources of signal-dependent noise during isometric force production. J Neurophysiol. *88*, 1533–1544.

Kasuga, S., Hirashima, M., and Nozaki, D. (2013). Simultaneous processing of information on multiple errors in visuomotor learning. PLoS One *8*, e72741.

Kawato, M. (2002). Cerebellum and motor control. The handbook of brain theory and neural networks, edited by Arbib MA. Cambridge, MIT Press, 190–195.

Kawato, M., Furukawa, K., and Suzuki, R. (1987). A hierarchical neural-network model for control and learning of voluntary movement. Biol. Cybern. *57*, 169–185.

Kim, H.E., Morehead, R., Parvin, D.E., Moazzezi, R., Ivry, R.B., (2018) Invariant errors reveal limitations in motor correction rather than constraints on error sensitivity. Commun. Biol. 1:19.

Kitazawa, S., Kimura, T., and Yim, P.B. (1998). Cerebellar complex spikes encode both destinations and errors in arm movements. Nature *392*, 494-497.

Körding, K.P., Wolpert, D.M. (2004). Bayesian integration in sensorimotor learning. Nature *427*, 244–247.

Korenberg, A.T., and Ghahramani, Z. (2002). A Bayesian view of motor adaptation. Curr. Psychol. Cogn. *21*, 537–564.

Kouh, M., and Poggio, T. (2008). A canonical neural circuit for cortical nonlinear operation. Neural Comput. *20*, 1427-51.

Louie, K., and Glimcher, P.W. (2012). Efficient coding and the neural representation of value. Ann. N. Y. Acad. Sci. *1251*, 13–32.

Louie, K., and Glimcher, P.W. (2019). Normalization principles in computational neuroscience. In: Oxford Research Encyclopedia of Neuroscience. Oxford University Press.

Louie, K., Grattan, L.E., and Glimcher, P. W. (2011). Reward value-based gain control: Divisive normalization in parietal cortex. J. Neurosci. *31*, 10627–10639.

Ma, W.J., Beck, J.M., Latham, P.E., and Pouget, A. (2006). Bayesian inference with probabilistic population codes. Nat. Neurosci. *9*, 1432–1438.

Ma, W.J. and Jazayeri, M. (2014). Neural coding of uncertainty and probability. Annu. Rev. Neurosci. *37*, 205–220.

Marko, M.K., Haith, A.M., Harran, M.D., and Shadmehr, R. (2012). Sensitivity to prediction error in reach adaptation. J. Neurophysiol. *108*, 1752–1763.

Ohshiro, T., Angelaki, D.E., and DeAngelis, G.C. (2011). A normalization model of multisensory integration. Nat. Neurosci. *14*, 775–782.

Ohshiro, T., Angelaki, D.E., and DeAngelis, G.C. (2017). A neural signature of divisive normalization at the level of multisensory integration in primate cortex. Neuron *95*, 399–411.

Olsen, S.R., Bhandawat, V., and Wilson, R.I. (2010). Divisive normalization in olfactory population codes. Neuron *66*, 287–299.

Pouget, A., Beck, J.M., Ma, W.J., and Latham, P.E. (2013). Probabilistic brains: knowns and unknowns. Nat. Neurosci. *16*, 1170–78.

Rabinowitz, N.C., Willmore, B., Schnupp, J.W.H., and King, A.J. (2011). Contrast gain control in auditory cortex. Neuron *70*, 1178–1191.

Reynolds, J.H., and Heeger, D.J. (2009). The normalization model of attention. Neuron *61*,

168–185.

Sato, T.K., Haider, B., Häusser, M., and Carandini, M. (2016). An excitatory basis for divisive normalization in visual cortex. Nat. Neurosci.*19*, 568–570.

Shadmehr, R., Smith, M.A., and Krakauer, J.W. (2010). Error correction, sensory prediction, and adaptation in motor control. Annu. Rev. Neurosci. *33*, 89–108.

Scheidt R. A., Reinkensmeyer, D.J., Conditt, M.A., Rymer, W.Z., Mussa-Ivaldi, F.A. (2000). Persistence of motor adaptation during constrained, multi-joint,arm movements. J Neurophysiol. 84, 853– 862.

Soetedjo, R, Kojima, Y, and Fuchs, A.F. (2008). Complex spike activity in the oculomotor vermis of the cerebellum: a vectorial error signal for saccade motor learning? J. Neurophysiol. *100*, 1949–1966.

Tsay, J.S., Avraham, G., Kim, H.E., Parvin, D.E., Wang, Z., and Ivry, R.B. (2021). The effect of visual uncertainty on implicit motor adaptation. J. Neurophysiol. *125*, 12–22.

Vaziri, S., Diedrichsen, J., and Shadmehr, R. (2006). Why does the brain predict sensory consequences of oculomotor commands? Optimal integration of the predicted and the actual sensory feedback. J. Neurosci. *26*, 4188–4197.

Wolpert, D.M., Ghahramani, Z., and Jordan, M.I. (1995). An internal model for sensorimotor integration. Science *269*, 1880–1882.

Webb, R., Glimcher, P.W., and Louie, K. (2014). Rationalizing context-dependent preferences: divisive normalization and neurobiological constraints on choice. SSRN Electronic Journal 2462895

Wei, K., and Körding, K. (2009). Relevance of error: what drives motor adaptation? J. Neurophysiol. *101*, 655–664.

Wei, K., and Körding, K. (2010). Uncertainty of feedback and state estimation determines the speed of motor adaptation. Front. Comput. Neurosci. *4*, 1