

NEUROSCIENCE

Overcoming the ceiling effects of experts' motor expertise through active haptic training

M. Hirano^{1,2*}, M. Sakurada^{1,2}, S. Furuya^{1,2}

One of the most challenging issues among experts is how to improve motor skills that have already been highly trained. Recent studies have proposed importance of both genetic predisposition and accumulated amount of practice for standing at the top of fields of sports and performing arts. In contrast to the two factors, what is unexplored is how one practices impacts on experts' expertise. Here, we show that training of active somatosensory function (active haptic training) enhances precise force control in the keystrokes and somatosensory functions specifically of expert pianists, but not of untrained individuals. By contrast, training that merely repeats the task with provision of error feedback, which is a typical training method, failed to improve the force control in the experts, but not in the untrained. These findings provide evidence that the limit of highly trained motor skills could be overcome by optimizing training methods.

INTRODUCTION

Overcoming the limits of expertise in experts plays a vital role in winning a gold medal at the Olympics or prizes at music competitions. A challenge among experts is therefore to improve motor skills that have been optimized through years of extensive training. The amount of accumulated time engaged in deliberate practice activities is one key factor for mastery of fine motor skills (1) but, counterintuitively, has a large amount of residuals to account for experts' exceptional motor expertise (2–4). To account for the residuals, recent studies have focused on the importance of the interaction between heredity and deliberate practice (4, 5). By contrast, a key but unexplored factor is the way of practicing (6), such as through differential learning that specifically enhances both speed and physiological efficiency in piano performance in expert players (7). It is thus possible that how one practices substantially affects the training effects on expertise in experts. This hypothesis predicts that specialized training, but not ordinal practice such as mere repetitions of a task, improves the motor skills of experts.

One candidate for such specialized training is sensory training because sensory functions play key roles in both the acquisition and execution of skillful actions (8, 9). The central nervous system corrects and updates motor outputs for the production of fine movements according to explicit sensory information representing the error in task performance (10, 11). In this case, highly trained motor skills eventually reach a ceiling in performance once errors in task performance are reduced to the amount smaller than one's error detection threshold or when errors are estimated on the basis of biased/inaccurate sensory functions. However, the deliberate practice targeting sensory functions is difficult for individuals to perform because one cannot access explicit feedback on errors or accuracy of sensory information. This can be a bottleneck for further improvement in expertise of experts. We thus postulate that sensory training facilitates fine motor control in experts. In particular, somatosensory functions play essential roles in fine control of movements (12). Previous studies demonstrated that loss of these functions degrades fine motor skills (13, 14) and individuals who have practiced

dexterous movements since childhoods (e.g., expert musicians) have superior somatosensory functions to untrained individuals (15). In addition, a somatosensory function in musicians still has the potential to be changed by unique somatosensory experiences (16). However, these studies focused primarily on passive somatosensory functions, which are not associated with fine motor control of experts (17). Compared to the passive somatosensory functions, active somatosensory functions during producing movements are more likely tied to fine motor control because somatosensory information is modulated by self-generated movements in a task-dependent manner (18–20). Our recent studies demonstrated that somatosensory-motor integration functions, but not passive somatosensory functions, are associated with fine motor control in expert pianists (21). These findings raise the possibility that specialized somatosensory training designed to enhance active somatosensory functions specifically facilitates fine motor control of experts to an extent that ordinal training is incapable of achieving.

Here, we hypothesized that the ceiling effect of experts' motor expertise is surmounted specifically through having a specialized training targeting the active somatosensory function. This hypothesis predicts firstly that the training that enhances the active somatosensory function improves fine motor control in experts who have undergone years of extensive piano training since childhood, secondly that the improved motor skill is beyond the level achieved by ordinal motor training, and thirdly that motor training enhances fine motor control of untrained individuals but not of expert individuals (i.e., ceiling effect). Assessing the specific effects of this specialized training indicates the potential that experts' skills do not reach their physical limits and that they are capable of improving by optimizing their training methods.

RESULTS

Three experiments were performed to test whether specialized somatosensory training specifically facilitates both somatosensory and motor skills in well-trained individuals. In total, 74 expert pianists and 25 musically untrained healthy individuals participated in the study. All pianists majored in piano performance in a musical conservatory and/or had extensive and continuous private piano training under the supervision of a professional pianist/piano

Copyright © 2020
The Authors, some
rights reserved;
exclusive licensee
American Association
for the Advancement
of Science. No claim to
original U.S. Government
Works. Distributed
under a Creative
Commons Attribution
NonCommercial
License 4.0 (CC BY-NC).

¹Sony Computer Science Laboratories Inc. (SONY CSL), Tokyo, Japan. ²Sophia University, Tokyo, Japan.

*Corresponding author. Email: hiraramasa@gmail.com

professor. To remove the effects of auditory feedback on the performance of all experimental tasks, we used a mute piano and instructed each participant to perform each behavioral task while listening to white noise from headphones worn on the ears.

Experiment 1

The purpose of experiment 1 was to test, first, whether intensive active somatosensory training improves somatosensory function even in pianists who have undergone years of extensive piano training since childhood and, second, whether such training also facilitates fine motor control in the pianists. Thirty-six expert pianists participated in the experiment, which consisted of a pretest, intervention, posttest, and retention test.

Training

Participants were divided randomly into three groups with different interventions: the training group [$n = 12$, 20.6 ± 1.7 years old (mean \pm SD)], the control group ($n = 12$, 22.2 ± 2.8 years old), and the rest group ($n = 12$, 19.6 ± 0.7 years old). The participants in the training group performed somatosensory training using a haptic device (Geomagic Touch X, 3D Systems Inc.) (“active haptic training”). Participants were instructed to strike a piano key, to which the haptic device was attached (Fig. 1A), twice in succession at a peak key descending velocity amounting to 50% of the maximum peak velocity of the key descending movements (MVK) by the right ring finger. A warning message of “too weak” or “too strong” was displayed on a monitor put in front of the participants if the peak key descending velocity was outside 35 to 65% of the MVK. During the active haptic training, the haptic device increased the key weight during either the first or second keystroke by pulling up the key (Fig. 1B). After performing the two keystrokes, participants were instructed to answer which keystroke was perceived heavier. Following each trial, we provided visual feedback on whether the answer was correct or incorrect (i.e., performance success). The active haptic training consisted of 20 blocks, each of which had 20 trials. In the first block, the haptic device loaded the key to the amount predetermined by the somatosensory test done before the training. To maintain task difficulty and facilitate perceptual learning during the training session, the load for the next block was reduced 10% from the load for the previous block when participants answered more than 80% trials within a block correctly. The participants in the control group struck a piano key with the right ring finger 400 times every 3 to 4 s at a peak key descending velocity of 50% of the MVK. Following each keystroke, the participants received visual feedback about the peak key descending velocity of the performed keystroke. We instructed each participant to strike the key at approximately the target velocity without imposing strict accuracy demands because the training of the control group was designed to examine whether repetitive somatosensory inputs derived from the keystrokes could enhance the somatosensory function and fine motor control of the pianists. The participants in the rest group rested for 30 min without any training. Before, after, and 30 min after the intervention (i.e., the pre-, post0, and post30 sessions), each participant underwent a somatosensory test and two motor tests.

Somatosensory test

The somatosensory test involved asking each participant to perform a weight detection task that assessed the point of subjective equality (PSE) as to changes in the key weight when striking the piano key at

a peak key descending velocity amounting to 50% of the MVK with the right ring finger. The haptic device increased the weight of the key by pulling it upward with a force of one of various predetermined levels (0.1 to 1.4 N in steps of 0.1 N) once each keystroke was commenced. Participants indicated whether they perceived the key being struck was heavier than an unloaded key, the weight of which was memorized through 20 keystrokes before the experiment. Figure 1 (D to F) shows the probability of answering “feeling heavier than the unloaded key” as a function of each load that was added externally. Each curve represents the result obtained from each session (i.e., the pre, post0, and post30 sessions). The psychometric curve of the post0 and post30 sessions appears to shift leftward compared with that of the pre-session in the training group but not the rest or control group. To quantify the shift, group means of the PSE at each of the three sessions were plotted for the three groups (Fig. 1C and fig. S1A). Two-way mixed analysis of variance (ANOVA) yielded a significant interactive effect between the group and session factors on PSE ($F_{3,7,61,13} = 5.06$, $P < 0.01$). Multiple comparison tests with Shaffer’s modified sequentially rejective Bonferroni procedure confirmed a significant difference in PSEs at the post0 ($t = 7.12$, $P < 0.01$) and post30 ($t = 4.17$, $P < 0.01$) sessions compared to that at the pre-session, and in PSEs at the post0 session compared to that at the post30 session ($t = 3.01$, $P = 0.01$) for the data from the training group but not for the data from the rest (pre-session versus post-sessions: $t = 2.56$, $P = 0.08$; pre versus post30: $t = 2.34$, $P = 0.08$; post versus post30: $t = 1.20$, $P = 0.26$) and control groups (pre-session versus post-sessions: $t = 0.98$, $P = 0.35$; pre versus post30: $t = 0.48$, $P = 0.64$; post versus post30: $t = 0.45$, $P = 0.20$). Furthermore, there were significant differences in the PSEs at the post0 session between the training group and rest group ($t = 2.82$, $P < 0.01$) and between the training and control groups ($t = 3.69$, $P < 0.01$). The PSE at the pre-session did not differ among the groups (training versus rest: $t = 0.14$, $P = 1.00$; training versus control: $t = 0.42$, $P = 1.00$; $t = 0.55$, $P = 1.00$). These results indicate that active haptic training, but not mere repetitive somatosensory inputs derived from the keystrokes, improved the pianists’ perception of heaviness.

To examine whether the attention level and keystroke kinematics when assessing the PSE differed among the three groups, we further analyzed the time course of (i) the median value of the reaction time (RT) between the keystroke and response across trials and of (ii) the mean peak velocity across keystrokes. Neither the RT (fig. S2A; two-way ANOVA, group: $F_{2,33} = 0.13$, $P = 0.88$; session: $F_{1,5,49,5} = 58.16$, $P < 0.01$; interaction: $F_{3,49,5} = 2.53$, $P = 0.07$) nor peak keystroke velocity (fig. S2B; two-way mixed ANOVA, group: $F_{2,33} = 1.20$, $P = 0.31$; session: $F_{2,66} = 1.33$, $P = 0.27$; group \times session interaction: $F_{4,66} = 0.95$, $P = 0.44$) differed between the groups, indicating that neither the attention level nor the keystroke kinematics differed between the groups at any of the sessions.

Motor tests

We assessed both the accuracy and agility indices of the finger keystroke movements in the motor tests. First, we asked each participant to repetitively strike a piano key using the right ring finger as fast as possible for 4 s. We calculated the number of strikes per second as the agility index. Figure 1G and fig. S1B show the time courses of the agility index in the three groups. Although the agility index increased over the sessions in the three groups, there were no significant group differences at any of the sessions (two-way mixed ANOVA, session: $F_{1,67,55,17} = 11.01$, $P < 0.01$; group: $F_{2,33} = 1.75$,

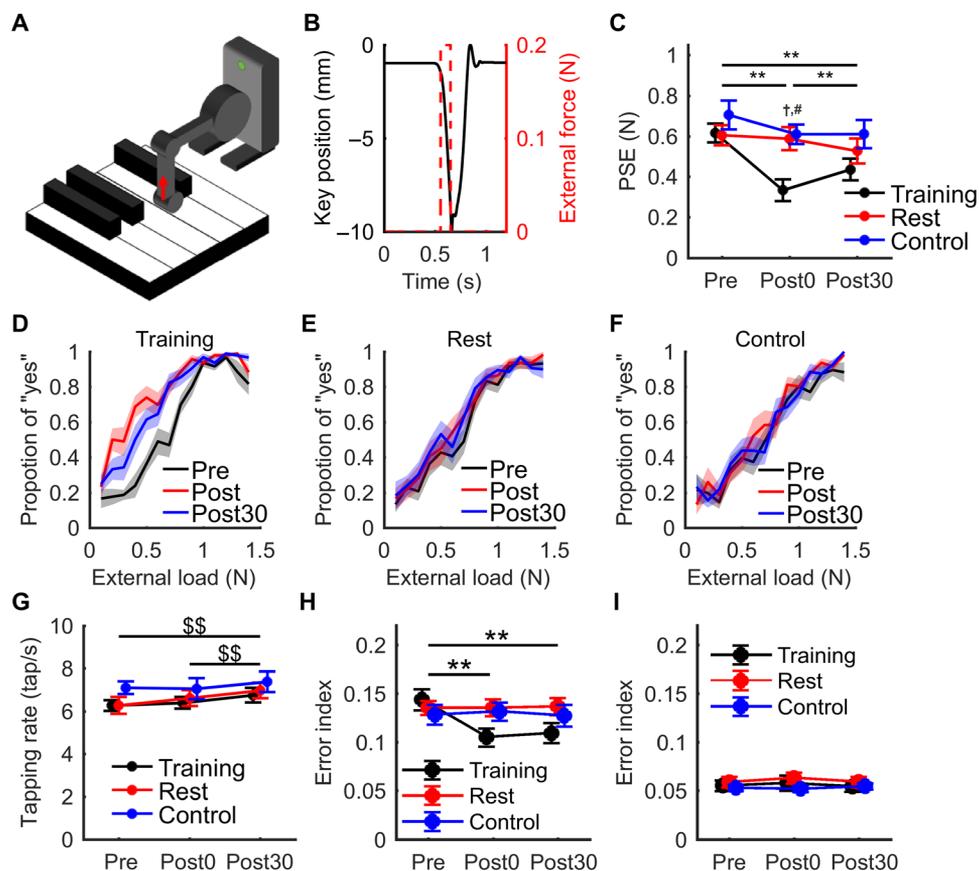


Fig. 1. Overview of the haptic system and results of experiment 1. (A) A three-dimensional model of the haptic system used in the present study. The haptic device was attached to a piano key and pulled the key during the key depression. (B) A representative data of how and when the haptic device loads the key during a keystroke. The black and red lines represent the vertical key motion of the piano key and the external load added to the piano key by the haptic device, respectively. The haptic device loaded the key during descending the key. (C) Group means of the point of subjective equality (PSE) at each of the three sessions are plotted for the three groups (black, training; red, rest; blue, control group). **Inter-session comparisons in the training group, $P < 0.01$. †Training versus rest group, $P < 0.01$. ‡Training versus control group, $P < 0.01$. (D to F) The probabilities of answering "feels heavier than the unloaded key" are plotted as a function of each external load added by the haptic device. Black, red, and blue lines represent the data obtained at the pre-, post0, and post30 sessions, respectively. The shaded areas show the range calculated by the mean \pm SEM. (G) Time courses of the tapping rate during the tapping task in the three groups (black, training; red, rest; blue, control group). \$\$Multiple comparisons for the main effect of the session factor, $P < 0.01$. (H and I) Time courses of the error index for the force production task in the three groups when the target was 30% (H) and 70% of the MVK (I). The small and large values indicate accurate and inaccurate performance, respectively. **Inter-session comparisons in the training group, $P < 0.01$.

$P = 0.19$; interaction: $F_{3,34,55,17} = 0.46$, $P = 0.73$). This confirmed no specific effect of the active haptic training on the movement agility of the trained finger. Second, we asked each participant to perform a force production task. In this task, the participants repetitively struck a piano key 20 times at a rate of 2 Hz using the right ring finger. They were instructed to produce either 30% (i.e., low-force production) or 70% (i.e., high-force production) of the MVK as accurately and consistently as possible. As an error index, we calculated a coefficient of variation of the peak key descending velocity across the last 10 strikes of each test. Three-way mixed ANOVA showed a significant second-order interaction effect among the group, session, and force level factors on the error index ($F_{4,66} = 3.34$, $P = 0.02$). Therefore, we split the data according to the force levels. In the low-force production condition (Fig. 1H and fig. S1C), the error index value decreased over the sessions in the training group but not in the rest and control groups (simple main effects test, training: $F_{2,22} = 21.41$, $P < 0.01$; rest: $F_{2,22} = 0.01$, $P = 0.99$; control: $F_{2,22} = 0.09$, $P = 0.92$). In contrast, in the high-force production con-

dition, the error index remained unchanged over the sessions and between the groups (two-way mixed ANOVA: group: $F_{2,33} = 0.63$, $P = 0.54$; session: $F_{2,66} = 0.34$, $P = 0.71$; interaction: $F_{4,66} = 0.38$, $P = 0.82$) (Fig. 1I and fig. S1D). These results indicate a specific improvement in the accuracy of the low-force production in the trained group.

Intervariable relations in experiment 1

First, to examine a relation between the baseline PSE and baseline error index of the low-force production task, we calculated a 95% confidence interval (CI) of the Pearson's correlation coefficient between these variables based on 1000 bootstrap samples. The CI ranged from -0.09 to 0.51 , which failed to confirm their correlation. With respect to the changes in the PSE and error index of the low-force production task through the training, there was also no correlation (CI: from -0.11 to 0.49). We further examined associations between participants' profiles and each of the baseline PSE and baseline error index. The bootstrapped regression analyses yielded

no covariation of the age at which pianists started to play the piano with each of the baseline PSE (CI: -0.42 to 0.22) and the baseline error index in any of the groups (CI: -0.24 to 0.43). In addition, the regression analysis detected no covariation of the total amount of piano training with those measures (baseline PSE: CI = -0.19 to 0.63 ; baseline error index: CI = -0.31 to 0.38).

Experiment 2

Experiment 1 demonstrated the effects of active haptic training but not repetitive keystrokes on both active somatosensory function and fine motor control of the trained finger in expert pianists. However, these results could not identify whether the training effects on fine motor control resulted from (i) the concurrent improvement of active somatosensory function, (ii) the mere repetitive performance of the discrimination task, or (iii) the internalization of the weight of the key. To identify this, pianists participating in experiment 2 were divided into two groups according to whether explicit feedback on performance success (i.e., reinforcement signals) was provided during active haptic training (FB and no-FB groups). Because the reinforcement signals play a role in driving perceptual learning (22, 23), we postulated that removing reinforcement signals (i.e., the no-FB group) prevents the improvement of active somatosensory function through active haptic training. In addition, we asked participants to perform the sensory and motor tests with the untrained index finger before and after the active haptic training performed with the ring finger to examine the transfer effects of active haptic training. If the weight of the key was internalized through the training, the training effects are predicted to transfer to the untrained finger. The purposes of experiment 2 were to address (i) whether reinforcement signals during active haptic training are necessary for enhancing active somatosensory function, (ii) whether the training effect on fine motor control depends on improvement of active somatosensory function, (iii) the transfer effects of active haptic training with the ring finger on the keystroke performed by the untrained finger, and (iv) the expertise dependence of the effect of active haptic training. Twenty-six expert pianists (eight pianists participated in experiment 1; the interval between the experiments 1 and 2 was at least 6 months) and 13 musically untrained individuals (nonmusicians) participated in this experiment.

Training

The pianists were divided into two groups: FB and no-FB groups. The pianists in the FB group ($n = 13$, 21.8 ± 1.9 years old) and the no-FB group ($n = 13$, 23.2 ± 4.7 years old) performed the active haptic training with and without the reinforcement signals. The nonmusicians performed the active haptic training with the reinforcement signals (NM group: $n = 13$, 27.5 ± 4.0 years old).

Somatosensory test

In experiment 1, we assessed the PSE of the change in the key weight as the heaviness perception. This procedure could not rule out the possibility that the active haptic training merely biased the participants to respond “perceive heavy” to the weight around their PSE. Furthermore, while the participants were required to memorize the weight of the unloaded key at the beginning of experiment 1, we did not confirm the stability of the memory of the unloaded key weight throughout the somatosensory test. These issues may increase the risk of a false alarm in the participant’s responses, which potentially underestimates the heaviness perception seen in

experiment 1. To exclude this possibility, experiment 2 used a weight discrimination task instead of the weight detection task used in experiment 1 to measure the heaviness perception threshold (PT). Participants were instructed to strike a key twice in succession at each trial. During only one of the two strikes, the haptic device increased the key weight to an amount determined by a staircase method (details are included in Materials and Methods). Subsequently, participants answered which keystroke they perceived as heavier. This procedure enabled us to assess the PT without being influenced by the response bias because it determined the PT based on the correctness of each response. We instructed each participant to perform this task under two keystroke conditions: (i) single keystrokes by the right index finger and (ii) single keystrokes by the right ring finger.

Figure 2A illustrates the time course of the PT for each group and for each keystroke condition. Three-way mixed ANOVA yielded a significant first-order interaction between the group and session factors on the PT ($F_{2,36} = 3.99$, $P = 0.03$). This indicates that the time course of the PT differed between the groups. We split the data by keystroke condition for additional analyses. In the ring finger keystroke condition, two-way mixed ANOVA followed by a simple main effect test identified a significant difference in the PT between the pre/posttests in the FB group ($F_{1,12} = 21.78$, $P < 0.01$) but not in the no-FB ($F_{1,12} = 0.24$, $P = 0.63$) and the NM ($F_{1,12} = 2.61$, $P = 0.13$) groups. By contrast, two-way mixed ANOVA yielded a significant main effect for the group factor for the PT for the index finger keystroke condition ($F_{2,36} = 6.06$, $P < 0.01$). Post hoc tests revealed significant differences in the PT between the FB and NM groups and between the no-FB and NM groups for the index finger condition (FB versus NM: $t = 3.44$, $P < 0.01$; no-FB versus NM: $t = 2.20$, $P = 0.03$). In summary, active haptic training with the reinforcement signals performed by the ring finger keystroke improved the PT of that finger in the pianists but not in nonmusicians. This training effect in the pianists did not generalize to the untrained index finger. Neither the median RT across trials (fig. S3A; three-way mixed ANOVA, group: $F_{2,36} = 0.03$, $P = 0.97$; group \times session interaction: $F_{2,36} = 1.36$, $P = 0.27$; group \times session \times time interaction: $F_{2,36} = 0.67$, $P = 0.52$) nor the mean peak velocity of key descending movements across trials (fig. S3B; three-way mixed ANOVA, group: $F_{2,36} = 0.92$, $P = 0.41$; group \times session interaction: $F_{2,36} = 0.16$, $P = 0.85$; group \times session \times time interaction: $F_{2,36} = 0.17$, $P = 0.84$) differed among the groups, indicating no differences in either the attention level or the keystroke kinematics among the groups.

Motor test

Before and after the training, we asked the participants to perform the low-force production task with (i) the right index finger and (ii) the ring finger. Figure 2B shows the time course of the error index for each keystroke condition. Three-way mixed ANOVA yielded a significant second-order interaction effect among the group, session, and condition factors for the error index ($F_{2,36} = 3.47$, $P = 0.04$). We thus split the data for each keystroke condition. In the ring finger keystroke condition, two-way mixed ANOVA followed by a simple main effect test identified that the error index value decreased over the sessions in the FB group (simple main effects test, $F_{1,12} = 14.62$, $P < 0.01$) but not in the no-FB ($F_{1,12} = 1.07$, $P = 0.32$) or NM group ($F_{1,12} = 0.34$, $P = 0.57$). Multiple comparison tests further revealed significant group differences in the error index at both the pretest (FB $<$ NM, $t = 3.26$, $P < 0.01$; no-FB $<$ NM, $t = 4.55$,

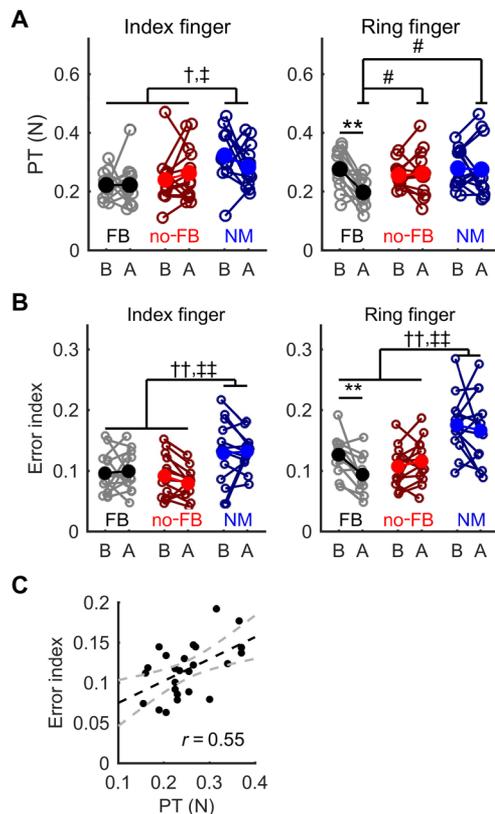


Fig. 2. Results of the sensory and motor tests in experiment 2. (A and B) The PTs assessed by the weight discrimination task (A) and the error index assessed by the low-force production task (B) in the three groups (black, FB; red, no-FB; blue, NM groups). The left and right panels show the results for the index finger and the ring finger, respectively. “B” and “A” displayed on the axis of abscissa indicate “before training” and “after the training,” respectively. Each thin line represents individual data, and each bold line indicates group mean data. **Inter-session comparisons in the training group, $P < 0.01$. † and ‡ indicate results of the main effect of the group factor, # indicates results of the multiple comparison in the post-session, and * indicates results of the inter-session comparison in the FB group. $P < 0.05$. ††No-FB versus NM groups for the main effect of the group factor, $P < 0.05$, $P < 0.01$. (C) A scatter plot between the PT and error index of the low-force production task at the pre-session in the pianist. The black dashed line indicates a regression line, and the gray dashed lines represent the 95% CI of the regression.

$P < 0.01$) and posttest (FB < NM, $t = 4.30$, $P < 0.01$; no-FB < NM, $t = 2.99$, $P < 0.01$). In contrast, for the index finger condition, two-way mixed ANOVA yielded a significant main effect of the group factor ($F_{2,36} = 7.07$, $P < 0.01$) but not of the session factor ($F_{1,36} = 0.11$, $P = 0.74$) and interaction effect of the two factors ($F_{2,36} = 0.78$, $P = 0.47$). Multiple comparison tests further revealed significant group differences in the error index at both the pretest (FB < NM, $t = 2.62$, $P = 0.01$; no-FB < NM, $t = 3.65$, $P < 0.01$) and posttest (FB < NM, $t = 4.30$, $P < 0.01$; no-FB < NM, $t = 2.99$, $P < 0.01$). These results confirmed that, similar to the somatosensory function, fine motor control was enhanced by active haptic training with the reinforcement signals only for the trained finger in the pianists.

Intervariable relations in experiment 2

First, we examined a relationship between the PT and the error index of the force production task at the pre-session in the pianist groups (i.e., both FB and no-FB groups). We calculated a 95% CI of

the Pearson’s correlation coefficient obtained from 1000 bootstrap samples. The CI ranged from 0.27 to 0.74 (i.e., above 0), indicating a positive correlation between the two variables (Fig. 2C). This indicates that pianists whose PT was lower exhibited a lower error index during the force production task at the pre-session. However, there was no correlation between the change in the PT and change in the error index through training in the training group (CI: -0.60 to 0.38). Next, to examine the possibility that the active haptic training was effective only for participants whose PT and error index were poor, we assessed the correlation between the baseline value and rate of a change between pre- and post-sessions for both the PT and error index in the training group. The bootstrap CI of the correlation coefficient was -0.88 to 0.11 for the PT and -0.83 to 0.36 for the error index. A lack of evidence that both CIs are above 0 confirmed no correlations in both the PT and error index. Last, we analyzed the participant’s profiles and behavioral measures. In the pianist groups, there were no correlations between the age at which pianists started to play the piano and each of the baseline PT (CI: -0.47 to 0.19) and the baseline error index (CI: -0.19 to 0.49). Similarly, the total amount of piano training did not correlate with the baseline PT (CI: -0.43 to 0.35) and baseline error index (CI: -0.36 to 0.73). Here, data from the trained finger were used for these analyses.

Experiment 3

Experiments 1 and 2 demonstrated improvements in both the somatosensory function and fine motor control of the finger that underwent active haptic training with the reinforcement signals in expert pianists but not nonmusicians. However, it remains unclear whether the fine motor control of pianists has already reached a ceiling in performance. Experiment 3 tested this by asking 12 expert pianists (23.2 ± 5.9 years old; two participated in experiment 2, and the interval between experiments 2 and 3 was at least 6 months) and 12 nonmusicians (29.5 ± 8.6 years old) to repeat the low-force production task 100 times with instructions to produce the target force as accurately as possible, and at each repetition, they received explicit feedback information on the error index. Before and after fine motor training, we assessed the error index of the task performed with the right ring and index fingers. We tested a hypothesis that the feedback error training of the force production task improves the error index only in the nonmusicians but not in the pianists.

Motor test

Figure 3 shows the time course of the error index for the low-force production task with the index finger keystroke and the ring finger keystroke. Three-way mixed ANOVA identified a significant first-order interaction effect between the group and session factors ($F_{1,22} = 5.63$, $P = 0.03$) and significant main effects of the group factor ($F_{1,22} = 15.88$, $P < 0.01$), the finger factor ($F_{1,22} = 15.97$, $P < 0.01$), and the session factor ($F_{1,22} = 5.21$, $P = 0.03$) for the error index value. Post hoc simple main effect tests revealed a significant difference in the error index value between the pre- and post-sessions in the nonmusicians ($F_{1,11} = 12.74$, $P < 0.01$) but not the pianists ($F_{1,11} < 0.01$, $P = 0.95$). Moreover, the error index of the pianists was lower than that of the nonmusicians both at the pre-session ($F_{1,22} = 21.00$, $P < 0.01$) and post-session ($F_{1,22} = 4.98$, $P = 0.04$). The results indicate firstly that the fine motor control of the pianists was superior to that of the nonmusicians even after the training and secondly that the error was reduced through

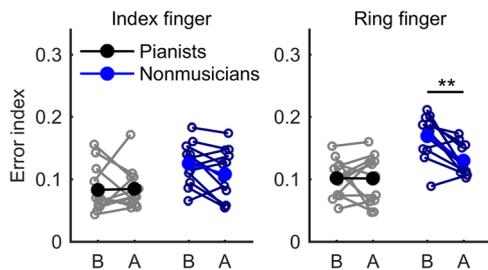


Fig. 3. The error index assessed by the low-force production task before and after motor training in experiment 3. Each colored line represents the groups (black, pianists; blue, nonmusicians), and the left and right panels show the results for the index finger and the ring finger, respectively. *, **Inter-session comparisons in the nonmusicians group, $P < 0.05$, $P < 0.01$.

the training of the motor task itself only in the nonmusicians but not in the pianists.

DISCUSSION

The present study examined the effects of somatosensory training on active somatosensory function and motor skills in both trained and untrained individuals. Our specialized somatosensory training (i.e., active haptic training) discriminating differences in the key weight by using a haptic device resulted in the improvement of active somatosensory function in the trained finger (the training group in experiment 1 and the FB group in experiment 2) but not the untrained finger (the FB group in experiment 2), even in the trained pianists. Such an improvement was absent when the active haptic training did not accompany the reinforcement signals (the no-FB group in experiment 2) in the pianists. These findings indicate that the improvement of somatosensory function in the pianists was specific to the finger that underwent active haptic training with reinforcement signals. This active haptic training failed to enhance the somatosensory function of the nonmusicians, which further indicates the specificity of the current training to the trained individuals. Furthermore, along with the improvement of somatosensory function in the trained finger, the active haptic training improved the fine motor control of the trained finger. In contrast to active haptic training, the motor training with provision of feedback information about the error index improved fine motor control only in the nonmusicians but not in the pianists, but the improved fine motor control of the nonmusicians was still inferior to that of the pianists (experiment 3). This suggests that the fine motor control of expert pianists has already reached its ceiling that cannot be overcome through the ordinal motor training with the piano. Together, our findings indicate that there still remains latitude for improvement of both active somatosensory and motor functions even in highly skilled individuals who have years of extensive dexterity training. This provides new perspectives, particularly that the present specialized somatosensory training has unique potential for overcoming limits of somatosensory function and fine motor control in highly trained individuals.

Improvement of somatosensory function through active haptic training

We demonstrated improvement in the active somatosensory function of pianists through active haptic training. The pianists who participated

in the present study had daily piano practice for many years, which means that their fingertips received abundant somatosensory inputs derived from the keystrokes through everyday training. This likely induces use-dependent plasticity (24), as exemplified first by the differences in both passive and active somatosensory function between the pianists and nonmusicians (16, 17, 21) and second by the absence of a significant correlation between the PT and the onset age of piano practice. A lack of enhancement of somatosensory function with repetitive somatosensory input (i.e., control group of the experiment 1 and no-FB group of the experiment 2) suggests that experts' active somatosensory functions relevant to the trained skill are robust against use-dependent learning based on repetitive somatosensory inputs. Conversely, a previous study demonstrated plastic changes in the passive somatosensory function of a finger in both musicians and nonmusicians using repetitive mechanical stimulation of the fingertip (16). While the previous study assessed the passive spatial acuity of the fingertip by a two-point discrimination task, the present study measured active somatosensory function by the musically relevant piano keystroke task. In contrast, the somatosensory function improved by active haptic training only when the pianists received reinforcement signals, which highlights the important role of feedback in perceptual learning. A theory of perceptual learning posits that reinforcement neural signals that originate as a result of task performance enhance the processing of neuronal activities relevant to the task stimulus (23, 25, 26). During normal piano practice, pianists have no access to explicit feedback information about the weight of a piano key. Therefore, the explicit reinforcement signals during active haptic training provide a unique opportunity for pianists to refine the somatosensory function responsible for active heaviness perception on a trial-by-trial basis, which enables them to overcome the limits to improvement derived from daily piano training. An alternative possibility is that the acquisition of explicit and precise knowledge about the key weight or the key movement dynamics through active haptic training facilitated somatosensory function. However, this is unlikely since the training effect did not generalize to the untrained finger.

An important observation was that the training effect was evident only in the pianists and not in the nonmusicians. This expertise-dependent effect of active haptic training on somatosensory function could be associated with the metaplasticity of the sensorimotor system. Previous studies have demonstrated a larger learning gain in musicians than nonmusicians, suggesting higher capacities for neuroplastic reorganization in trained individuals (i.e., metaplasticity) (27, 28). According to the concept of metaplasticity, active haptic training induces neural reorganization more effectively in pianists than in nonmusicians, which fits with the present results. This can be mediated by the expertise-specific somatosensory-motor integration (21) and internal representation of the musical instrument (29, 30) in the pianists. An alternative explanation is that there is a difference in fine motor control between pianists and nonmusicians (31). The somatosensory task used in the present study required both striking the key twice per trial and comparing the weight perceived by the two keystrokes. A precise comparison of the weight through the two keystrokes necessitates keystrokes with low force variability. A failure to produce the force accurately in nonmusicians may thus disrupt performance and learning of the somatosensory task in unskilled individuals. Therefore, we propose that the somatosensory training should be done after fine motor control is sufficiently improved by motor training, such as the feedback error training used in the experiment 3.

Improvement of fine motor control

There is growing evidence that interventions that enhance somatosensory function facilitate motor learning and performance in young people (32–35), elderly people (36), and patients with movement disorders (37, 38). In contrast to these previous studies that focused mostly on untrained individuals, the present study first demonstrated that active haptic training facilitates fine motor control and enhances active somatosensory function in trained individuals.

The present study focused on expert pianists because their fine motor control is sophisticated and may well reach a ceiling in performance through years of extensive piano training since childhood. This is supported by the findings that the fine motor control of the pianists was superior to the nonmusicians and the motor training involving the low-force production task with provision of error feedback, which was effective for nonmusicians, failed to improve the fine motor control of pianists (i.e., experiment 3). Thus, such an ordinal training can only improve motor skills that are in the midst of being sophisticated but has the limit for further improvement of well-trained motor skills, i.e., a ceiling effect. A question is what causes the ceiling effect. The present findings propose that the active somatosensory function is one candidate bottleneck of enhancing the fine motor control in expert pianists. Motor control and learning relies heavily on corrective mechanisms based on errors between perceived and expected motor actions. Error correction operates appropriately when motor actions are perceived accurately on the basis of the active somatosensory function. This is supported partly by the correlational relationship between fine motor control and the active but not passive somatosensory functions demonstrated in our previous (17, 21) and present studies (i.e., experiment 2). We also showed that fine motor control was improved through the active haptic training in experts only if the training accompanied the enhancement of active somatosensory function. It is thus possible that the active haptic training enhances the active somatosensory function and then improved the fine motor control in experts by providing accurate motor error feedback during movements. Active haptic training improved the performance of the force production task in the pianists when the target velocity was 30% but not 70% of the MVK. There are at least two possible mechanisms that explain this. One possibility is a difference in the task difficulty of the force production task used in this study between the two force levels. We found that the error index in the high-force production task was much lower than that of the low-force production task. Thus, it is likely that the high-force production task was easier to perform than the low-force production task, which may explain the observed difference between the conditions. Another possibility is the difference in the degree of the sensory modulation, which is defined as attenuation or enhancement of somatosensory afferent inputs during self-generated movements (19, 39), between the two force levels. A previous study demonstrated that the degree of sensory modulation is associated with the force production levels; specifically, there is higher attenuation for lower force levels, and no attenuation for high force levels (40). This suggests that sensory modulation altered somatosensory information derived from keystrokes specifically in the low-force production task, which could also affect force control based on somatosensory feedback. In other words, sensory modulation can be a bottleneck for fine motor control. Active haptic training can tune the somatosensory function to reduce the perceptual error between actual and perceived key weight during keystrokes due to sensory

modulation and eventually facilitate fine motor control. Because the degree of sensory modulation was originally low for the high-force production task, the performance of this task remained unchanged throughout the training. Thus, active haptic training improves well-trained motor skills by removing a bottleneck factor that blocks further performance improvements specifically for highly skilled individuals.

Last but not least, note that these results were based on the simplified piano keystroke task. Therefore, a challenging but intriguing question is whether the present results can be replicated when performing tasks more similar to the real piano performance involving sequential finger movements with presence of auditory somatosensory interactions.

CONCLUSION

The present study firstly provided novel evidence that enhancement of somatosensory functions through specialized somatosensory training improves a well-trained motor skill, specifically for musicians who had years of instrument training. A lack of such skill enhancement through conventional piano practice in the experts further suggests that the present training provides a unique means for overcoming the limits of well-trained motor skills.

MATERIALS AND METHODS

Participants

In total, 74 healthy pianists and 25 nonmusicians participated in the three experiments. All of the pianists majored in piano performance at a musical conservatory and/or had extensive and continuous private piano training under the supervision of a professional pianist and/or a piano professor. All participants gave their written informed consent before the experiments. All experimental procedures were carried out in accordance with the Declaration of Helsinki and were approved by the ethics committees of Sony Corporation and Sophia University. To remove the effects of auditory feedback on the performance of all experimental tasks, we muted a piano and instructed each participant to perform each behavioral task while listening to white noise from headphones worn on the ears.

Haptic piano system

To assess the active sensing of the heaviness of a piano key, we developed a novel haptic system connected to a piano key. A haptic device (Geomagic Touch X, 3D Systems) was attached to a piano key using a custom-made fixing tool (hereafter, this key is called the “haptic key”). The haptic device could generate forces up to 7.9 N in any direction in three-dimensional space. Three optical encoders built into the device were used to measure the haptic key position (spatial resolution, 0.023 mm) and velocity at 1000 Hz. The upward vertical force pulling up the haptic key was generated by the device, which was servo-controlled at 1000 Hz to aggravate the key during key depression.

Recording of movements of a piano key

The vertical motion of the piano key was measured using an optical distance sensor put under the key at a sampling rate of 500 Hz. The sensor values were low-pass filtered (fourth-order zero-lag Butterworth filter, cut-off frequency: 24 Hz) and differentiated to obtain the velocity values.

Experiment 1

Experiment 1 was designed to test, first, whether intensive active somatosensory training improves active somatosensory function even in pianists (active haptic training) who had undergone years of extensive piano training since childhood and, second, whether such training also facilitates fine motor control in the pianists.

Protocol

Thirty-six expert pianists participated in this experiment. They were assigned to three groups: the training group ($n = 12$), the rest group ($n = 12$), and the control group ($n = 12$). At the beginning of the experiment, we asked each participant to strike a piano key as forcefully as possible with the right ring finger to measure the MVK. There was no significant difference in the MVK among the three groups (one-way ANOVA, group: $F_{2,35} = 0.20$, $P = 0.82$). The participants in the training group underwent active haptic training designed to improve the somatosensory function of the right ring fingertip. Before and after the training (i.e., pre-session and post-session) and 30 min after the training (i.e., retention session), one somatosensory test and two motor tasks were performed with the right ring finger: a weight detection task that assessed a PSE about the changes in the weight of a piano key, a fastest finger tapping task, and a force production task that assessed how accurately participants could produce a predetermined peak velocity of key movements. The participants in the control group struck a piano key with the right ring finger 400 times every 3 to 4 s at a key descending velocity of 50% of the MVK. Following each keystroke, the participants received visual feedback about the key descending velocity. The participants in the rest group rested for 30 min without undergoing active haptic training.

Somatosensory test

We assessed somatosensory function by measuring the PSE based on a weight detection task. Participants were instructed to strike the key connected to the haptic device at a keystroke velocity of 50% of the MVK with the right ring finger when the color of a circle displayed on a monitor put in front of them changed from gray to red. During each key depression, the haptic device pulled the key up to increase the key weight. Following the keystroke, participants were instructed to indicate whether the key to be depressed was perceived as heavier than the unloaded key or not by pressing one of two buttons, which corresponded to “yes” or “no,” with the left hand. A warning message of either “weak” or “strong” was displayed on the monitor if the key descending velocity was not within the range of 35 to 65% of the MVK.

The somatosensory test consisted of memorization and test sessions. First, there was a memorization session in which participants were instructed to strike the unloaded key 20 times and to memorize the weight of the unloaded key. Following the memorization session, a test session was initiated, in which the key weight was increased during each trial during the keypress by one of 14 different loads (0.1 to 1.4 N in steps of 0.1 N) that was randomly selected. Each load was provided eight times during the test session. We calculated the probability of load detection (a ratio of “felt heavier” responses) and fitted these data with a cumulative Gaussian distribution function (probability of detection as a function of the load) to identify the PSE. Here, the PSE was defined as the load at which the load detection probability was 50% on the fitted function. During the test session, we included the unloaded condition 10 times every 20 keystrokes so that the participants could keep memorizing the weight of the unloaded key.

Active haptic training

During the training session, each participant in the training group performed a weight discrimination task. The training consisted of 20 blocks, each of which had 20 trials. Participants were instructed to strike the key twice in succession with the right ring finger at a key descending velocity of 50% of the MVK. A warning message of “too weak” or “too strong” was displayed on a monitor in front of the participants if the key descending velocity was outside 35 to 65% of the MVK. The haptic device increased the key weight during either the first or second keystroke. After performing the two keystrokes, participants were instructed to indicate which keystroke was perceived as heavier. Depending on whether the answer was correct, a blue circle or a red cross was displayed on the monitor to provide explicit visual feedback on performance success. In the first block, the haptic device loaded the key to the amount predetermined by the somatosensory test done before the training. To maintain task difficulty and to facilitate perceptual learning during the training session, the load of the next block was reduced 10% from the load of the previous block when participants answered correctly for more than 80% of trials within a block.

Behavioral measurements

Force production task

The force production task aimed to assess the accuracy of force production for repetitive piano keystrokes. The participants repetitively struck the key 20 times at a rate of 2 Hz with the right ring finger for each trial. They were instructed to produce either 30 or 70% of the MVK. During the first 10 keystrokes, the participants received visual feedback about the peak velocity value of each keystroke, which was then removed during the subsequent 10 keystrokes. We calculated a coefficient of variation for the peak velocity values for these last 10 keystrokes as an index of the force production accuracy. We repeated this task over five trials and calculated an average value of this index across the trials.

Finger tapping task

The finger tapping task assessed the agility of the repetitive finger movements. Each participant repeatedly struck a piano key as fast as possible for 4 s with the right ring finger. We instructed the participants to voluntarily immobilize the other fingers on the adjacent four keys. We calculated the number of taps per second as an index of the finger movement speed.

Experiment 2

Experiment 2 tested first whether the improvement in fine motor control through active haptic training seen in experiment 1 depended on improvement in active somatosensory function; second, whether the effect of active haptic training depends on expertise; and, third, whether the effects of active haptic training on the fine motor control of the trained finger could generalize to other fingers and movements.

Protocol

Twenty-six expert pianists and 13 nonmusicians participated in this experiment. The pianists were assigned randomly into two groups: the FB group ($n = 13$) and the no-FB group ($n = 13$). The participants in the FB and no-FB groups performed the active haptic training with and without provision of explicit feedback information on performance success (i.e., correctness of the answer to the weight discrimination task). The nonmusicians performed the active haptic training with explicit feedback information on performance success.

Before and after the training, the participants performed both somatosensory tests and force production tasks with each of the right ring and index fingers.

Somatosensory test

In experiment 2, we measured the PT for weight discrimination by a staircase method. We used this method instead of measuring the psychometric curve used in experiment 1 because the staircase method was able to detect the PT quicker than identifying the psychometric curve, which is necessary for experiment 2, which contained two somatosensory tests with different conditions. Participants were instructed to strike the key twice with the right ring or index finger. During only one of the two keystrokes, the haptic device increased the key weight to the amount determined according to the staircase method (details follow). Following the two keystrokes, participants answered which keystroke was perceived as heavier. The order of both the amount of the load and which keystroke was to be loaded was randomized across trials. The load was determined on the basis of a three-down one-up staircase method. The load in the first trial was set to 0.2 N. The load of the next trial was decreased or increased by 0.02 N, depending on whether correct answers were repeated three times or an answer was incorrect once, respectively. The task was finished when four peaks and four troughs were recorded. We defined the averaged value of the last two peaks and two troughs of the load as the PT of the two-weight discrimination.

Experiment 3

Experiment 3 tested whether motor training with the low-force production task and performance feedback enhances fine motor control to accurately produce a low force in both expert pianists and non-musicians and whether this skill reached a plateau in expert pianists.

Protocol

Twelve expert pianists and 12 nonmusicians participated in this experiment. The participants performed the force production task as accurately as possible with the right ring finger 100 times as the motor training. The target key descending velocity level was set to 30% of the MVK. During the training, the participants received explicit feedback about the force production accuracy at the end of each trial and were asked to minimize the amount of error in the force production. Before and after the training, the participants were asked to perform the force production task with the right index and ring fingers.

Statistics

All data were analyzed with MATLAB 2016b (MathWorks, MA, USA). Statistical tests were performed in R (version, 3.5.1). Mauchly's test was used to test for sphericity before running each ANOVA test. The Greenhouse-Geisser correction was used for nonspherical data. If a first-order interaction reached the threshold for significance ($P < 0.05$), then we first performed a simple main effects test. Then, a multiple comparison test with Shaffer's modified sequentially rejective Bonferroni procedure was used for the post hoc testing if a simple effect reached the threshold for significance.

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/6/47/eabd2558/DC1>

[View/request a protocol for this paper from Bio-protocol.](#)

REFERENCES AND NOTES

- W. R. Boot, K. A. Ericsson, *The Oxford Handbook of Cognitive Engineering: Expertise* (Oxford Univ. Press, 2013).
- B. N. Macnamara, D. Z. Hambrick, F. L. Oswald, Deliberate practice and performance in music, games, sports, education, and professions: A meta-analysis. *Psychol. Sci.* **25**, 1608–1618 (2014).
- D. Z. Hambrick, A. P. Burgoyne, B. N. Macnamara, F. Ullén, Toward a multifactorial model of expertise: Beyond born versus made. *Ann. N. Y. Acad. Sci.* 10.1111/nyas.13586 (2018).
- F. Ullén, D. Z. Hambrick, M. A. Mosing, Rethinking expertise: A multifactorial gene-environment interaction model of expert performance. *Psychol. Bull.* **142**, 427–446 (2016).
- E. J. Meinz, D. Z. Hambrick, Deliberate practice is necessary but not sufficient to explain individual differences in piano sight-reading skill: The role of working memory capacity. *Psychol. Sci.* **21**, 914–919 (2010).
- S. Furuya, Individual differences in sensorimotor skills among musicians. *Curr. Opin. Behav. Sci.* **20**, 61–66 (2018).
- S. Furuya, S. Yokota, Temporal exploration in sequential movements shapes efficient neuromuscular control. *J. Neurophysiol.* **120**, 196–210 (2018).
- D. J. Ostry, P. L. Gribble, Sensory plasticity in human motor learning. *Trends Neurosci.* **39**, 114–123 (2016).
- R. J. Zatorre, J. L. Chen, V. B. Penhune, When the brain plays music: Auditory-motor interactions in music perception and production. *Nat. Rev. Neurosci.* **8**, 547–558 (2007).
- R. S. Johansson, J. R. Flanagan, Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nat. Rev. Neurosci.* **10**, 345–359 (2009).
- D. A. Nowak, S. Glasauer, J. Hermsdörfer, How predictive is grip force control in the complete absence of somatosensory feedback? *Brain* **127**, 182–192 (2004).
- M. Omrani, C. D. Murnaghan, J. A. Pruszynski, S. H. Scott, Distributed task-specific processing of somatosensory feedback for voluntary motor control. *eLife* **5**, e13141 (2016).
- J. C. Rothwell, M. M. Traub, B. L. Day, J. A. Obeso, P. K. Thomas, C. D. Marsden, Manual motor performance in a deafferented man. *Brain* **105**, 515–542 (1982).
- N. Smania, B. Montagnana, S. Faccioli, A. Fiaschi, S. M. Aglioti, Rehabilitation of somatic sensation and related deficit of motor control in patients with pure sensory stroke. *Arch. Phys. Med. Rehabil.* **84**, 1692–1702 (2003).
- T. Elbert, C. Pantev, C. Wienbruch, B. Rockstroh, E. Taub, Increased cortical representation of the fingers of the left hand in string players. *Science* **270**, 305–307 (1995).
- P. Ragert, A. Schmidt, E. Altenmüller, H. R. Dinse, Superior tactile performance and learning in professional pianists: Evidence for meta-plasticity in musicians. *Eur. J. Neurosci.* **19**, 473–478 (2004).
- M. Hosoda, S. Furuya, Shared somatosensory and motor functions in musicians. *Sci. Rep.* **6**, 37632 (2016).
- L. G. Cohen, A. Starr, Localization, timing and specificity of gating of somatosensory evoked potentials during active movement in man. *Brain* **110**, 451–467 (1987).
- J. Confais, G. Kim, S. Tomatsu, T. Takei, K. Seki, Nerve-specific input modulation to spinal neurons during a motor task in the monkey. *J. Neurosci.* **37**, 2612–2626 (2017).
- W. R. Staines, S. J. Graham, S. E. Black, W. E. McLroy, Task-relevant modulation of contralateral and ipsilateral primary somatosensory cortex and the role of a prefrontal-cortical sensory gating system. *Neuroimage* **15**, 190–199 (2002).
- M. Hirano, Y. Kimoto, S. Furuya, Specialized somatosensory-motor integration functions in musicians. *Cereb. Cortex* **30**, 1148–1158 (2020).
- A. R. Seitz, H. R. Dinse, A common framework for perceptual learning. *Curr. Opin. Neurobiol.* **17**, 148–153 (2007).
- A. Seitz, T. Watanabe, A unified model for perceptual learning. *Trends Cogn. Sci.* **9**, 329–334 (2005).
- B. Godde, B. Stauffenberg, F. Spengler, H. R. Dinse, Tactile coactivation-induced changes in spatial discrimination performance. *J. Neurosci.* **20**, 1597–1604 (2000).
- A. R. Seitz, J. E. Nanez Sr., S. Holloway, Y. Tsushima, T. Watanabe, Two cases requiring external reinforcement in perceptual learning. *J. Vis.* **6**, 9 (2006).
- H. Makino, E. J. Hwang, N. G. Hedrick, T. Komiyama, Circuit mechanisms of sensorimotor learning. *Neuron* **92**, 705–721 (2016).
- E. Altenmüller, S. Furuya, Brain plasticity and the concept of metaplasticity in skilled musicians. in *Progress in Motor Control*, J. Laczko, M. L. Latash, Eds. (Springer, 2016), pp. 197–208.
- K. Rosenkranz, A. Williamson, J. C. Rothwell, Motorcortical excitability and synaptic plasticity is enhanced in professional musicians. *J. Neurosci.* **27**, 5200–5206 (2007).
- M. Lotze, Kinesthetic imagery of musical performance. *Front. Hum. Neurosci.* **7**, 280 (2013).
- H. Imamizu, T. Kuroda, S. Miyauchi, T. Yoshioka, M. Kawato, Modular organization of internal models of tools in the human cerebellum. *Proc. Natl. Acad. Sci. U.S.A.* **100**, 5461–5466 (2003).
- T. Oku, S. Furuya, Skilful force control in expert pianists. *Exp. Brain Res.* **235**, 1603–1615 (2017).
- J. D. Wong, D. A. Kistemaker, A. Chin, P. L. Gribble, Can proprioceptive training improve motor learning? *J. Neurophysiol.* **108**, 3313–3321 (2012).

33. K. Rosenkranz, J. C. Rothwell, Modulation of proprioceptive integration in the motor cortex shapes human motor learning. *J. Neurosci.* **32**, 9000–9006 (2012).
34. J. E. Aman, N. Elangovan, I.-L. Yeh, J. Konczak, The effectiveness of proprioceptive training for improving motor function: A systematic review. *Front. Hum. Neurosci.* **8**, 1075 (2015).
35. S. Uehara, I. Nambu, S. Tomatsu, J. Lee, S. Kakei, E. Naito, Improving human plateaued motor skill with somatic stimulation. *PLOS ONE* **6**, e25670 (2011).
36. A. A. Priplata, J. B. Niemi, J. D. Harry, L. A. Lipsitz, J. J. Collins, Vibrating insoles and balance control in elderly people. *Lancet* **362**, 1123–1124 (2003).
37. K. E. Zeuner, W. Bara-Jimenez, P. S. Noguchi, S. R. Goldstein, J. M. Dambrosia, M. Hallett, Sensory training for patients with focal hand dystonia. *Ann. Neurol.* **51**, 593–598 (2002).
38. P. Celnik, F. Hummel, M. Harris-Love, R. Wolk, L. G. Cohen, Somatosensory stimulation enhances the effects of training functional hand tasks in patients with chronic stroke. *Arch. Phys. Med. Rehabil.* **88**, 1369–1376 (2007).
39. C. E. Chapman, Active versus passive touch: Factors influencing the transmission of somatosensory signals to primary somatosensory cortex. *Can. J. Physiol. Pharmacol.* **72**, 558–570 (1994).
40. L. D. Walsh, J. L. Taylor, S. C. Gandevia, Overestimation of force during matching of externally generated forces. *J. Physiol.* **589**, 547–557 (2011).

Acknowledgments: We thank K. Shibata (RIKEN CBS) for providing constructive comments on an early version of the manuscript. **Funding:** This study was supported by JST CREST (JPMJCR17A3) and JSPS Grant-in-Aid for Scientific Research(B) (19H04020). M.H. was supported as a Research Fellow of JSPS (19J01734). **Author contributions:** Conceptualization: M.H. and S.F. Methodology: M.H. Investigation: M.H. and M.S. Writing (original draft): M.H. Writing (review and editing): M.H. and S.F. Funding acquisition: M.H. and S.F. **Competing interests:** M.H. and S.F. are inventors on a patent application related to this work filed by Sony Corporation (no. 2020020584, 10 February 2020). The authors declare that they have no other competing interests. **Data and materials availability:** All data needed to evaluate the conclusion in the paper are present in the paper and/or Supplementary Materials. Additional data related to this paper may be requested from the authors.

Submitted 10 June 2020

Accepted 6 October 2020

Published 20 November 2020

10.1126/sciadv.abd2558

Citation: M. Hirano, M. Sakurada, S. Furuya, Overcoming the ceiling effects of experts' motor expertise through active haptic training. *Sci. Adv.* **6**, eabd2558 (2020).