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# Decomposition of a complex motor skill with precise error feedback and intensive training breaks expertise ceiling

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Yudai Kimoto <sup>1</sup>✉, Masato Hirano <sup>1,2</sup> & Shinichi Furuya <sup>1,2</sup>

Complex motor skills involve intricate sequences of movements that require precise temporal coordination across multiple body parts, posing challenges to mastery based on perceived error or reward. One approach that has been widely used is to decompose such skills into simpler, constituent movement elements during the learning process, thereby aligning the task complexity with the learners' capacity for accurate execution. Despite common belief and prevalent adoption, the effectiveness of this method remains elusive. Here we addressed this issue by decomposing a sequence of precisely timed coordination of movements across multiple fingers into individual constituent elements separately during piano practice. The results demonstrated that the decomposition training enhanced the accuracy of the original motor skill, a benefit not achieved through mere repetition of movements alone, specifically when skilled pianists received explicit visual feedback on timing error in the order of milliseconds during training. During the training, the patterns of multi-finger movements changed significantly, suggesting exploration of movements to refine the skill. By contrast, neither unskilled pianists who underwent the same training nor skilled pianists who performed the decomposition training without receiving visual feedback on the error showed improved skill through training. These findings offer novel evidences suggesting that decomposing a complex motor skill, coupled with receiving feedback on subtle movement error during training, further enhances motor expertise of skilled individuals by facilitating exploratory refinement of movements.

A common nature of skillful motor actions is fast and precise performance of sequential movements requiring dexterous control of multiple body parts. Mastering such skills poses challenges even for individuals who have undergone extensive training, due to the necessity for sequential and simultaneous execution of intricate movement elements. By contrast, a primary focus of motor learning research has been on simplistic motor tasks such as reaching for a target or walking, which limits unveiling learning principles underlying the mastery of complex skills such as sports and music performance. To solve this issue is increasingly significant, because unlike the prevailing belief<sup>1</sup>, recent studies have reported that the amount of practice only explains approximately 30% of expertise<sup>2–4</sup>, which requires improving ways of practicing. Furthermore, practicing overlearned motor skills potentially poses risks of triggering movement disorders such as focal dystonia<sup>5</sup>, which underscores the importance of elucidating methods for mastering complex skills efficiently.

One of the bottlenecks to learn complex motor skills lies in the intricate execution and perception of fast and accurate repetitions of complex movement elements. Motor skill learning typically relies on updating

movements based on error signals and/or reinforcement cues derived from task execution<sup>6–11</sup>. However, this learning process encounters limitations when the task complexity surpasses the learners' capacity for appropriate execution. One possible solution is to perform the complex motor skill at a submaximal speed so as to make the task executable and perceivable, which is effective for untrained individuals<sup>12</sup>. Another approach that has been widely used in motor training is to decompose intricate movement sequences into a set of simple elements, a method shown to facilitate learning of complex motor skills in untrained individuals<sup>13–15</sup>. It has also been documented that the nervous system represents decomposed elements of movements<sup>16</sup>, which changes plastically through learning<sup>17,18</sup>. Furthermore, motor skill acquisition appears to accelerate when a newly learned skill shares common elements with previously learned motor skills<sup>14</sup>, suggesting a possibility that learning constituent skills generalizes acquisition of the original motor skill. However, it remains unclear whether and in what manner motor skill decomposition during training aids in mastering complex motor skills, and even overcomes the ceiling effect of learning in trained individuals<sup>19</sup>. It is also possible that training with mere movement

<sup>1</sup>Sony Computer Science Laboratories Inc. (Sony CSL), Tokyo, Japan. <sup>2</sup>NeuroPiano Institute, Kyoto, Japan. ✉e-mail: [yudai.k36@gmail.com](mailto:yudai.k36@gmail.com)

decomposition does not enhance the overtrained motor skill, but is effective together with provision of augmented feedback of error that is subtle in skillful movements. However, mere provision of augmented error feedback in repetitive piano keystrokes was not effective for improving the motor skill of expert pianists<sup>20</sup>, highlighting the difficulty of breaking expertise ceiling.

Here, we tested it through practicing constituent elements of intricate motor sequences requiring precisely timed coordination of multiple fingers in piano playing. We hypothesized that training involving the decomposition of an intricate skill, coupled with the provision of error information, fosters exploration of movements during learning so as to enhance performance of the original complex skill, even in a task where conventional practice methods fail to yield further improvement.

## Results

Two experiments were performed to test whether the decomposition of a complex motor skill facilitates the learning of that skill. In total, 60 skilled and 12 non-skilled pianists participated in the study.

### Experiment 1

The purpose of experiment 1 was to test whether the skill decomposition in practicing, together with the visualization of subtle movement errors, facilitates the learning of a complex motor skill that is extremely difficult to perform even by pianists who have undergone years of extensive piano training since childhood. Thirty-six skilled and 12 non-skilled pianists participated in the experiment, which consisted of a pretest, intervention, and posttest sessions (Fig. 1A).

### Experimental task

The experimental task required the alternate repetition of two movement patterns of synchronous strikes of two keys (i.e. double third trills); one the right index and ring fingers (movement pattern A) and another with synchronous keystrokes with the right middle and little fingers (movement pattern B) (Fig. 1B-a). This task is obtained from Etude Op. 25 no. 6 composed by Frédéric Chopin, being known as one of the most technically demanding pieces. Each trial consists of successful repetition of one cycle of two movement patterns 20 times. If keypresses were performed in an incorrect order (e.g., pressing the keys with the index and little fingers instead of the middle and little fingers for the movement pattern B), those keypresses were not counted in the successful 20 repetitions, and that trial was considered an error trial. We asked the participants to repeat the experimental task 10 times in the pretest and posttest sessions with maintaining a predetermined fastest tempo for each individual, which was determined for each participant as one with the probability of the error trials being approximately 6 out of 10 trials. As an index of the motor performance, we counted the number of the error trials among the 10 trials (i.e., keypress error).

### Training

To confirm the ceiling effect of the conventional training on the complex motor skill, we conducted the repetition training of the experimental task. Twelve skilled pianists were instructed to play as quickly as possible while minimizing the probability of the error occurrence [9 women,  $22.3 \pm 2.7$  years old]. The training of the repetition of the experimental task consisted of 30 trials, each of which had 20 strikes of the keys. They took a 3-min break every 5 trials.

Another 24 skilled pianists were randomly divided into two groups with different interventions: the feedback (FB) group [skilled FB group:  $n = 12$ , 1 man,  $22.9 \pm 2.3$  years old (mean  $\pm$  SD)] and the no-FB group [ $n = 12$ , 5 men,  $21.8 \pm 2.1$  years old]. All non-skilled pianists were allocated to the FB group [non-skilled FB group,  $n = 12$ , 2 men,  $23.7 \pm 5.6$  years old]. All participants individually practiced two movement patterns, which were constituent elements of the experimental task (Fig. 1B-b). One involved the synchronous strikes of two piano keys leaving one white key in between with the index and ring fingers while releasing the two depressed keys adjacent to the keys to be struck with the middle and little fingers at the same time (i.e.,

movement pattern A). Another (movement pattern B) is the inversion of the movement pattern A (i.e. keystrokes with the middle and little fingers and key-releases with the index and ring fingers). In the training session, participants in the FB and no-FB groups were instructed to execute each movement pattern discretely, with synchronizing the timing of the movements across four fingers (Fig. 1A-b). Following the execution, the participants in the FB group received visual feedback regarding the timing of each finger movement (i.e. temporal synchrony of movements between the fingers). The visual feedback information included the onset of keypress by each of the four fingers within a time window of 0–100 ms. In addition, if the difference in the timing between the earliest and latest finger movements (i.e., timing error) is lower than 10 ms or larger than 20 ms, circles corresponding to each finger displayed in the monitor turned black or blue, respectively; otherwise, it turned red. Thus, these three colors roughly indicated the amount of error. The participants were instructed to minimize the timing error based on the visual FB throughout the training session. The participants in the no-FB group were instructed to minimize the timing error without provision of the visual FB solely based on the tactile information at the keypresses. The training of each movement pattern consisted of 10 blocks, each of which had 30 trials. The participants took a 5-min break every 5 blocks. Half of the participants practiced the movement pattern A first and then practiced the pattern B, whereas another half practiced the movement patterns in the opposite order.

Before and after the training session (i.e., pretest and posttest sessions), all participants (i.e., participants of repetition and decomposition trainings) underwent the experimental task to assess the change in the task performance.

### Performance of the experimental task

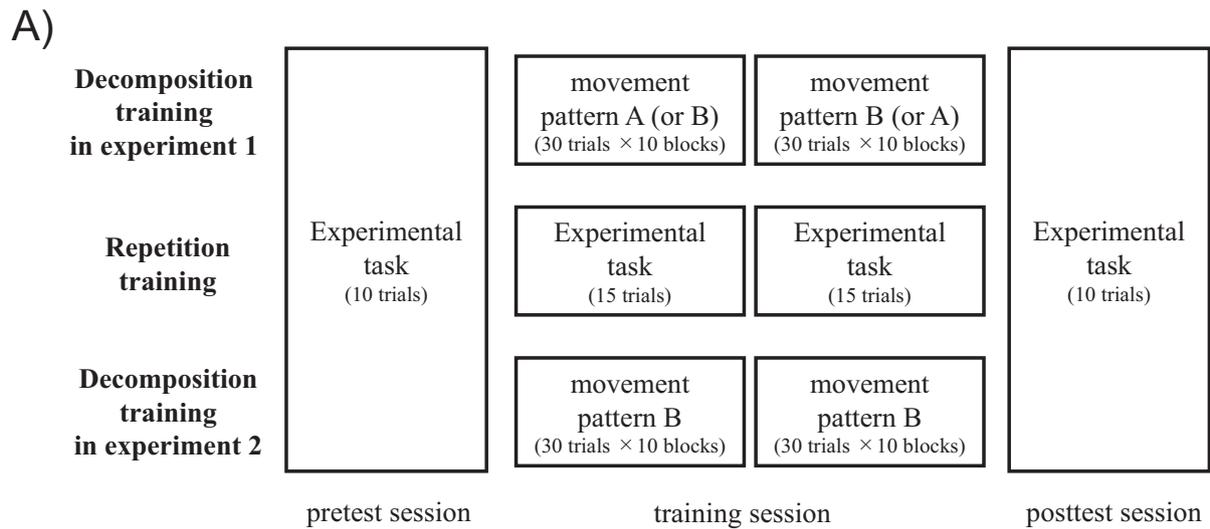
Figure 2A illustrates the mean values of the keypress error across the skilled pianists who underwent the repetition training of the experimental task in each of the pretest and posttest sessions. To confirm the repetition training effect on the motor performance, we used a generalized linear mixed effect model (GLME) with a Poisson distribution because it was a count data (fixed effect: session; random effect: participant). The GLME did not yield a significant difference in the keypress error between the pretest and posttest sessions ( $\chi^2 = 3.1$ ,  $P = 0.08$ ).

Figure 2B illustrates the group means of the keypress error in each of the pretest and posttest sessions for the skilled FB, no-FB, and non-skilled FB groups. The results confirmed that the keypress error in the pretest session did not differ across all groups. This is because the movement tempo was personalized so that the probability of error trial could become 60% for each participant. To assess the decomposition training effect on the motor performance, we used a GLME with a Poisson distribution (fixed effects: group, session, and their interaction; random effect: participant). The GLME identified a significant interaction effect between the factors ( $\chi^2 = 6.8$ ,  $P = 0.03$ ). A simple effect test unveiled a significant reduction in the keypress error specifically in the skilled FB group ( $z$  ratio =  $-2.7$ ,  $P < 0.01$ ). Moreover, we calculated a mean value of the interval between repeated keystrokes of the two movement patterns in each trial of the experimental task, in order to verify whether the movement tempo changes between the pretest and posttest sessions. We used a GLME with a logarithm link function and a gamma distribution (fixed and random effects were same as the keypress error) due to non-negative values and the distribution skewing towards 0. The GLME showed no significant difference in the movement tempo between the sessions ( $\chi^2 = 1.5$ ,  $P = 0.21$ ).

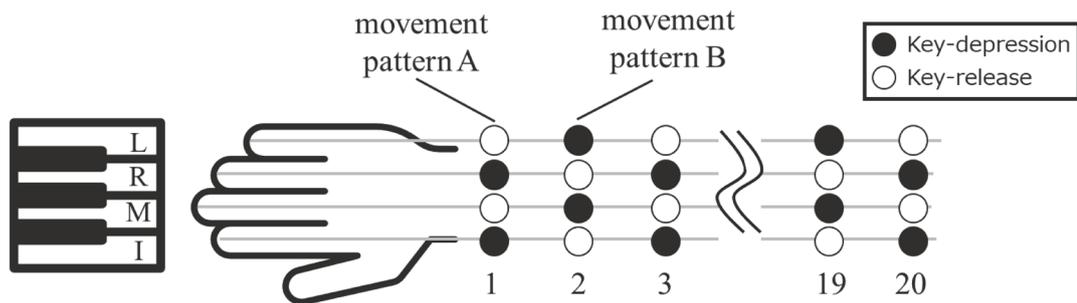
In summary, the skilled FB group showed an improvement in probability of the error occurrence while maintaining the movement tempo. On the contrary, the repetition training of the experimental task and the decomposition training in each of the skilled pianists without error feedback and in the non-skilled pianists did not show such improvement.

### Timing error

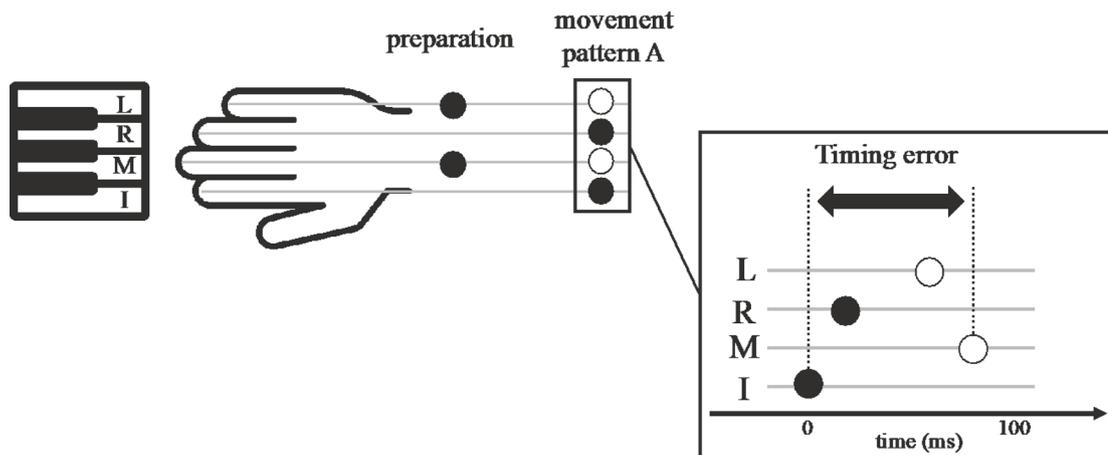
Figure 2C (a), (b) illustrate the time course of the timing error derived from the training session for the movement patterns A and B in the skilled FB, no-



**B) (a)** Experimental task in pretest and posttest sessions



**(b)** Decomposition training



FB, and non-skilled FB groups. To test whether the timing error was changed through training based on the difference in the timing error at block 1, we used a GLME with a logarithm link function and a gamma distribution (fixed effects: group, block, movement pattern, and their interactions; covariate: timing error at block 1; random effects: participant, participant×block, participant×movement pattern). A GLME yielded main

effects of group ( $\chi^2 = 10.2, P < 0.01$ ) and timing error at block 1 ( $\chi^2 = 137.9, P < 0.01$ ), and an interaction effect between group and block factors ( $\chi^2 = 35.5, P < 0.01$ ) on the timing error. A post hoc test revealed significant group differences in the timing error at the block 5 (skilled FB < non-skilled FB:  $z$  ratio =  $-3.2, P < 0.01$ ), at the block 6 (skilled FB < non-skilled FB:  $z$  ratio =  $-2.6, P = 0.02$ ), at the block 7 (skilled FB < no-FB:  $z$  ratio =  $-3.0,$

**Fig. 1 | The overview of the experiments.** **A** Experimental procedure of the Experiments 1 and 2. Participants underwent either the decomposition training or repetition training of the experimental task. The participants who underwent the decomposition training took a 5-min break every 5 blocks, whereas the participants who underwent the repetition training took a 3-minute break every 5 trials. All participants performed the experimental task before and after the training. **B** (a) Experimental task. The task required the alternate repetition of two movement patterns. Each pattern consists of synchronous strikes of two keys with releasing another two keys; one using the right index and ring fingers for the strikes (movement pattern A) and another using the right middle and little fingers for the strikes (movement pattern B). I, M, R, and L indicate the index, middle, ring, and little fingers, respectively. (b) Skill decomposition training with visual feedback on the

timing error of synchronous key motions with the four fingers. The training required practicing each of the two constituent movement patterns separately. For example, when practicing the pattern A, each participant kept depressing the keys with the middle and ring fingers during the preparation phase. Once the cue was provided, these two fingers lifted the keys whereas both the index and ring fingers depressed the adjacent keys synchronously. Participants in the skilled and non-skilled FB groups received the visual feedback (FB) on the timing of the key depression and key release by each of the four fingers within a time window of 0–100 ms (a sublet). When the difference in the timing between the initial and last key motions (timing error in the sublet) was lower than 10 ms or larger than 20 ms, circles corresponding to each finger displayed in the monitor turned black or blue, respectively; otherwise, it turned red. Each participant was instructed to minimize the timing error.

$P < 0.01$ ; skilled FB < non-skilled FB:  $z$  ratio =  $-3.4$ ,  $P < 0.01$ ), at the block 9 (skilled FB < no-FB:  $z$  ratio =  $-3.1$ ,  $P < 0.01$ ; skilled FB < non-skilled FB:  $z$  ratio =  $-3.8$ ,  $P < 0.01$ ), and at the block 10 (skilled FB < no-FB:  $z$  ratio =  $-3.3$ ,  $P < 0.01$ ; skilled FB < non-skilled FB:  $z$  ratio =  $-3.9$ ,  $P < 0.01$ ). This indicates the timing error was reduced through the training of both the movement patterns specifically in the skilled FB group.

Figure 2D (a, b) illustrate the group means of the timing error derived from the pretest and posttest sessions for the movement patterns A and B in the skilled FB, no-FB, and non-skilled FB groups. To confirm the decomposition training effect on the timing error during the experimental task, we used a GLME with a logarithm link function and a gamma distribution (fixed effects: group, session, movement pattern, and their interactions; random effects: participant, participant  $\times$  session, participant  $\times$  movement pattern). The GLME yielded a significant main effect of the movement pattern ( $\chi^2 = 6.0$ ,  $P = 0.01$ ), but neither group nor session effects.

In summary, for the skilled FB group, the result of the training showed improvement of the timing error in both movement patterns A and B, whereas the training effect on the timing error did not reach it during the experimental task.

## Experiment 2

Experiment 1 demonstrated that the decomposition of complex motor skill with provision of the visual FB on the error information in training improved the timing error for both movement patterns during training session and the keypress error of the complex skill in the skilled pianists. By contrast, the result of the experimental task showed no improvement in the timing error for both movement patterns. The lack of improvement may be attributed to the number of trials, although this aspect remains unclear. Moreover, we found the reduction of the keypress error by the decomposition training, whereas the underlying mechanism remains unclear. To clarify these, in Experiment 2, we asked participants to intensively practice movement pattern B, which turned out to be more challenging than movement pattern A (because the timing error of the experimental task was larger in the movement pattern B than in the movement pattern A) and examined the effects of training on the kinematics of multi-finger movements. Twenty-four skilled pianists participated in Experiment 2, where they were trained solely on movement pattern B while recording the angle of the metacarpophalangeal (MCP) and proximal interphalangeal (PIP) joints of 4 fingers using a data glove implementing sensors recording the joint angles (Fig. 1A).

## Experimental task

Some participants in the skilled FB group in Experiment 1 showed no error in the task performance after the training. To prevent this floor effect, the participants in Experiment 2 performed the experimental task with a movement tempo that was confirmed to elicit approximately 8 error trials out of 10 trials at preliminary investigation done prior to the pretest session, indicating an increased task difficulty Experiment 2 compared to Experiment 1.

## Training

Participants were randomly divided into two groups with different interventions: the FB group [ $n = 12$ , 4 men,  $26.6 \pm 5.3$  years old] and the no-FB group [ $n = 12$ , 1 man,  $22.9 \pm 4.2$  years old]. Based on the results that

facilitation of the exploration of the movement pattern B correlated with improvement in the motor performance, the participants in both the FB and no-FB groups were instructed to perform the movement pattern B with and without the visual FB regarding the timing of the finger movements in the same manner as Experiment 1. Both the FB and no-FB groups underwent a training session consisting of 600 trials (30 trials  $\times$  20 blocks) and took a 5-minute break every 5 blocks. In addition to the measurement of the piano keystrokes, we also measured the MCP and PIP joint angles of the 4 fingers using the data glove during the pretest, posttest, and training sessions.

## Performance of the experimental task

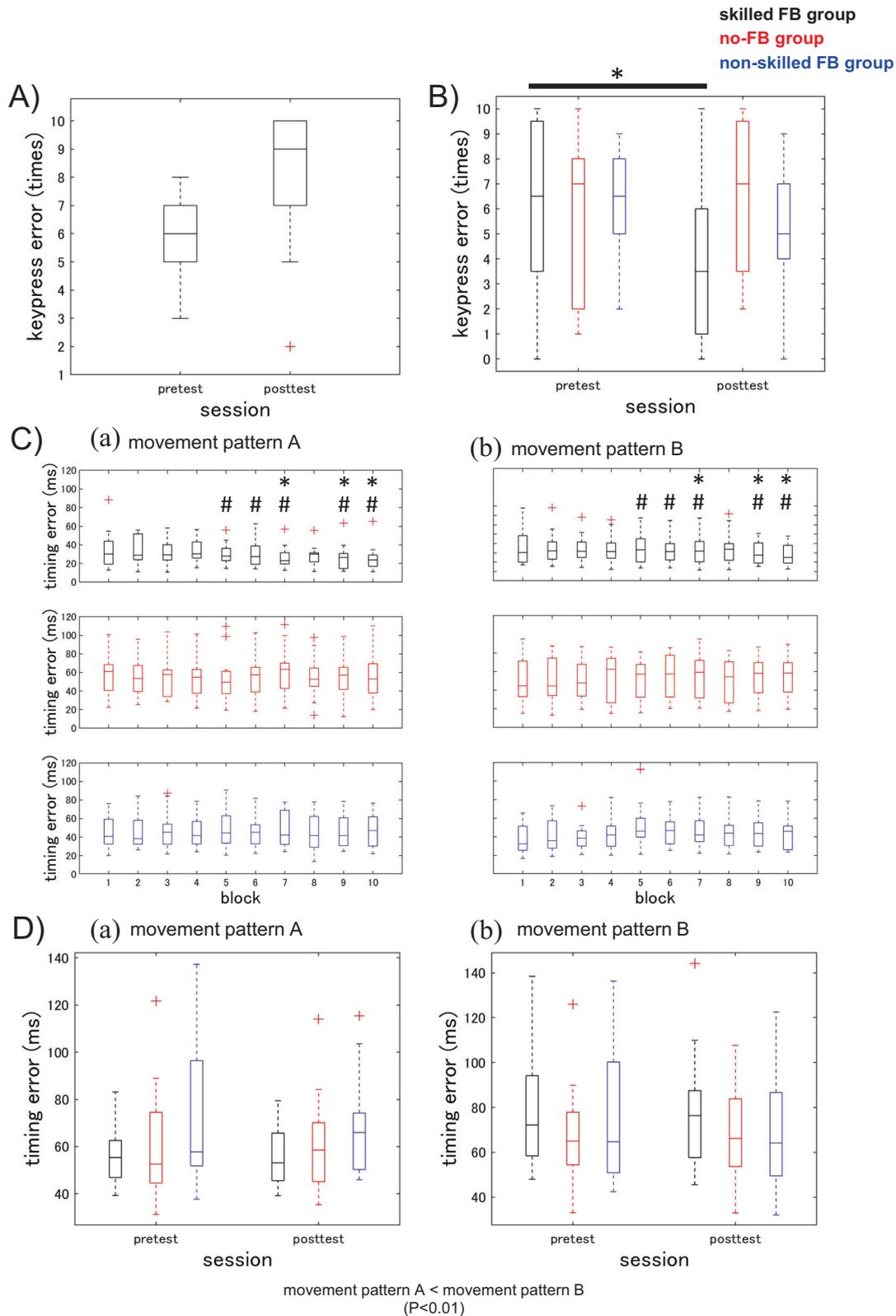
Figure 3A illustrates the group means of the keypress error in the pretest and posttest sessions for both groups. This value in the pretest session was higher in Experiment 2 than Experiment 1, reflecting the increased task difficulty in Experiment 2. A GLME with a Poisson distribution for the keypress error (fixed effects: group, session, and their interaction; random effect: participant) yielded significant main (group:  $\chi^2 = 6.1$ ,  $P = 0.01$ , session:  $\chi^2 = 10.4$ ,  $P < 0.01$ ) and interaction (group  $\times$  session:  $\chi^2 = 6.0$ ,  $P = 0.01$ ) effects. Post hoc tests identified significant improvement of the keypress error through the training specifically in the FB group ( $z$  ratio =  $-3.9$ ,  $P < 0.01$ ) but not in the no-FB group ( $z$  ratio =  $-1.0$ ,  $P = 0.35$ ).

Figure 3B, C illustrates the group means of the timing error for the movement patterns A and B in the pretest and posttest sessions for both groups. A GLME with a logarithm link function and a gamma distribution (fixed effects: group, session, movement pattern, and their interactions; random effects: participant, participant  $\times$  session, participant  $\times$  movement pattern) revealed a significant interaction effect between session and movement pattern factors ( $\chi^2 = 10.6$ ,  $P < 0.01$ ). Post hoc tests found a significant session-wise difference in the timing error for the movement pattern B ( $z$  ratio =  $-2.3$ ,  $P = 0.02$ ), but not the movement pattern A ( $z$  ratio =  $-0.4$ ,  $P = 0.72$ ).

## Changes in the finger joint movements

Because the decomposition training simplifies intricate movements so that they can be executed and perceived, it is postulated that the exploration of the finger movements is facilitated during the learning process. To test this hypothesis, we assessed changes in the finger joint movements throughout the training. Figure 3D, E illustrates averaged time-varying finger joint angles across 600 trials in the training session at one representative pianist of each group. Positive and negative values indicate extension and flexion of the finger joints, respectively. A shaded area of the time course of the finger joint angles, which represents the variance across trials, was larger for a pianist of the FB group than for one of the no-FB group.

To quantify the amount of the exploration during the training session, we first computed the angular velocities (Fig. 3F, G: same pianist as in Fig. 3D, E, respectively) and then computed the amount of change in the angular velocities between two consecutive training blocks. Specifically, we first calculated the average peak angular velocity of each finger joint across trials for each training block. Thus, one vector consisting of angular velocity values of the eight finger joints was computed for each block (i.e., 20 vectors in total). Then, we computed the Euclidean distances in the angular velocity vector between all possible pairs of two adjacent training blocks (i.e., 19



pairs). This reflects the time course of the change in finger joint movements between adjacent blocks. We refer this value as a variability index (VI). A high VI value indicates different patterns of the finger joint movements between the two blocks (i.e., large exploration), whereas a low VI value indicates performing similar finger joint movements between the two blocks (i.e., low exploration).

Figure 3H illustrates the group mean of the VI in the FB and no-FB groups. A linear mixed effects model (LME: fixed effects: group, block, and their interactions; random effects: participant) revealed significant main (group:  $\chi^2(1) = 4.0, P = 0.04$ ; block:  $\chi^2(18) = 69.29, P < 0.01$ ) and interaction effects between the factors ( $\chi^2(18) = 59.1, P < 0.04$ ). Post hoc tests yielded group differences in the VI at each of the block 1 ( $t(344) = 3.4, P < 0.01$ ), at

**Fig. 2 | The results of the Experiment 1.** **A** Box plots of the keypress error across the skilled pianists who underwent the repetition training of the experimental task in the pretest and posttest sessions. The x-axis and y-axis indicate the session and the keypress error, respectively. There was no significant difference between the pretest and posttest, which confirmed no training effect of repeating the experimental task. **B** Box plots of the keypress error in the pretest and posttest sessions for the skilled FB (black), no-FB (red), and non-skilled FB (blue) groups. The x-axis and y-axis indicate the session and the keypress error, respectively. A horizontal line indicates a significant difference between the pretest and posttest in the group of the same color ( $P < 0.05$ ). **C** Box plots of the timing error of each of the two movement patterns (A, B) across 10 blocks in the skilled FB (black), no-FB (red), and non-skilled FB (blue)

groups. The x-axis and y-axis indicate the block and the timing error, respectively. Asterisk and hashtag indicate significant differences in the timing error between the FB group and each of the no-FB and non-skilled FB groups, respectively. **D** Box plots of the timing error of each of the two movement patterns (A, B) in pretest and posttest sessions in the skilled FB (black), no-FB (red), and non-skilled FB (blue) groups. The x-axis and y-axis indicate the session and the timing error, respectively. The timing error derived from the experimental task was higher for the movement pattern B compared with the movement pattern A ( $P < 0.05$ ), which indicates higher difficulty of executing the movement pattern B. Twenty-four right-handed skilled pianists (12 for each group) and 12 right-handed age-matched non-skilled pianists participated in the Experiment 1.

the block 2 ( $t(338) = 3.0, P < 0.01$ ), at the block 7 ( $t(338) = 3.4, P < 0.01$ ), at the block 8 ( $t(338) = 2.0, P = 0.03$ ), at the block 9 ( $t(338) = 3.0, P < 0.01$ ), and at the block 10 ( $t(338) = 3.0, P < 0.01$ ).

### A relation between finger joint coordination pattern and motor performance

To identify whether the amount of the exploration of the finger joint movements is associated with the improvement of the performance of the experimental task by the training, we computed Pearson's correlation between the VI and the change in the keypress error between the pretest and post-test sessions. Overall, the VI was larger in the first few blocks than the subsequent blocks in the FB group, and was kept constant in the last few blocks in both groups. We thus used the difference in the VI between the blocks 1–2 and 19–20 for this analysis. Figure 3I illustrates the scatterplots of the differential value of the VI relative to the differential value of the keypress error in each of the FB and no-FB groups. We found a significant positive relationship between these variables specifically in the FB group ( $R = 0.66, P = 0.02$ ) but not in the no-FB group ( $R = 0.25, P = 0.44$ ).

### Discussion

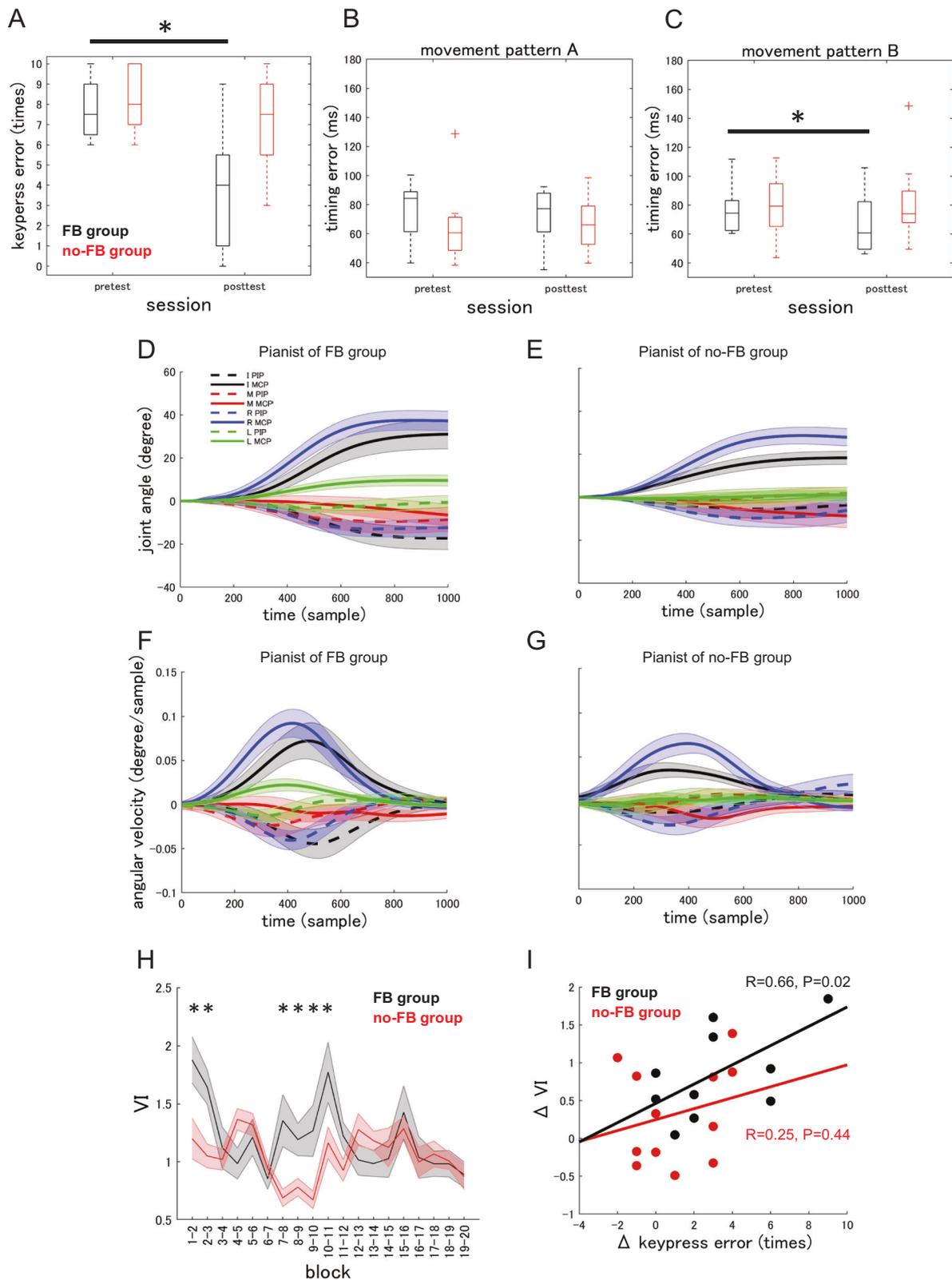
The present study tested whether decomposition of a complex motor skill into simple constituent skills in training enhanced the complex skills in skilled and non-skilled pianists. First, we found that mere repetition of a complex motor skill in practicing the piano failed to enhance the performance of this task in the skilled pianists, confirming the learning plateau. By contrast, practicing each of two simple constituent movement patterns separately, which were obtained by decomposing the target complex motor skill, yielded reduction of the error occurrence in skilled pianists, specifically when the visual feedback of the subtle error information was provided during the training. This indicates that the decomposition training with visual feedback of timing errors is an effective way to enhance complex motor skills that cannot be improved through the ordinal training. However, this training effect was not observed in the non-skilled pianists and even in the skilled pianists who received no explicit feedback on timing error. In addition, the training effect was evident when intensive training was performed with a challenging task. Further analyses based on the finger joint movements provided evidence of increases in the amount of movement exploration during training of one of the constituent movement patterns only in the FB group of the skilled pianists. This facilitation of movement exploration during training was correlated positively with the performance improvement. Our findings indicate that training with the skill decomposition and error augmentation facilitates the performance of complex motor skills specifically in the skilled individuals. Furthermore, the skill decomposition training uniquely enabled learners to explore the finger movements so as to reduce error in performing complex motor skill while maintaining constant movement tempo, which may reflect improvement in the speed-accuracy tradeoff of that skill.

Motor skill learning typically accompanies exploration to optimize the movements that can achieve a task goal. Previous studies have demonstrated that movement exploration emerges early in motor skill learning<sup>21–24</sup> and is associated with the learning rate<sup>7,25–27</sup>. However, movement exploration in learning can be largely constrained when the task complexity is high, since learners cannot accurately execute the task without elevating stiffness of the

limb muscles<sup>28,29</sup>. Thus, a lack of motor performance improvement when skilled pianists merely repeated the complex motor skill in practicing may be because the high complexity of the present motor task limited movement exploration due to an increased physical constraint on the movements. By contrast, movement exploration and performance were facilitated when skilled pianists practiced the simple movement elements derived from the decomposition of the complex skill. This suggests that breaking down complex skills into executable elements drives exploration of the movement in learning. This effect, however, was only evident when the performance of decomposed elements was visually fed back to the learners. Here, the feedback information to be provided included both precise timing error and abstract reinforcement signals that can be associated with reward (i.e. color representing success or failure of task performance). The reward signals have been demonstrated to facilitate the reinforcement learning that involves movement exploration<sup>27,30</sup>. It is therefore possible that the present pianists sought for discovering an optimal movement based on the error-related feedback. We also found that movement exploration occurred in the beginning of training, whereas the movement variability decreased as the training progressed. Thus, once a movement coordination pattern that can facilitate the performance is discovered in the early training phase, learners may switch from exploration to the strategy of further sophisticated movement<sup>21,31,32</sup>. Although the learning process that leverages movement variability has been also demonstrated in the bird song learning<sup>33,34</sup>, a common challenge among trained individuals is that reduced movement variability at the late stage of learning can be the bottleneck of movement exploration for further sophisticating the skill<sup>19</sup>. The present finding thus provides novel insights that the skill decomposition with augmented error feedback in learning overcomes this limit.

In this study, our aim was not only to enhance exploration during training but also to guide the learning via providing error feedback. It has been widely recognized that providing feedback on movement errors through various sensory modalities facilitates motor learning<sup>35</sup>, in which visual feedback has been commonly used. In our training that visually presents the timing of movements of the individual fingers after executing simple movement elements consisting of the complex motor skill, the skilled FB group showed a decrease of the timing error during training. Conversely, in Experiment 1, the timing error of motor performance in the experimental task was not changed following the entire training. This may be due firstly to the higher complexity of the experimental task compared to the decomposed elements during learning, and secondly to limited effects of the present decomposed training on the timing error of movements in performing the original experimental task. However, in Experiment 2 where the movement pattern B was specifically trained and the amount of the training was twice as much as one in Experiment 1, the timing error of the experimental task following the training was reduced specifically for the trained movement pattern B. These results suggest potential impacts of prolonged training of the decomposition elements with visual feedback on the original motor task.

The present training indicated expertise-dependent training effects on the exploration and motor performance. One reason why these changes did not manifest in the non-skilled group could be their lower finger dexterity. Our previous studies showed that skilled pianists are able to perform coordinated finger movements through adaptation in the biomechanical



and neuromuscular features of the hand<sup>36,37</sup>. In contrast, the non-skilled participants did not undergo such adaptations, which implies that even the decomposed movement elements were too difficult to be executed. Since the present constituent movement patterns require opposing movements of adjacent fingers synchronously, low independence of movement between the fingers, such as the middle and ring fingers, would make the task

performance difficult for the non-skilled individuals<sup>38-41</sup>. In fact, the timing errors during the training session were larger for the non-skilled FB group compared to the skilled FB group. The uncontrollably large movement variability during the task used for the training in the unskilled individuals may interfere volitional exploration of movements and/or exploitation of error information to update motor actions. Instead, such unskilled

**Fig. 3 | The results of the Experiment 2.** Box plots of the keypress error (A) in the pretest and posttest sessions in the FB (black) and no-FB (red) groups. The *x*-axis and *y*-axis indicate the session and the keypress error, respectively. A horizontal line indicates a significant session-wise difference in the group of that color ( $P < 0.05$ ). Box plots of the timing error (B, C) of each of the two movement patterns (A, B) in pretest and posttest sessions in the FB (black) and no-FB (red) groups. The *x*-axis and *y*-axis indicate the session and the timing error, respectively. A horizontal line indicates a significant session-wise difference in the group of that color ( $P < 0.05$ ). Averaged finger joint angles (D, E) and angular velocities (F, G) across 600 trials in one representative pianist of the FB group (left panel) and in another of the no-FB group (right panel). A solid and dotted line indicate the metacarpophalangeal and proximal interphalangeal joints of each of the index (black), middle (red), ring (blue), little (green) fingers. The *x*-axis and *y*-axis indicate the normalized time points and the

finger joint angles or the angular velocities, respectively. **H** Group means of the VI for the movement pattern B obtained from the angular velocity in the FB (black) and no-FB (red) groups. The *x*-axis and *y*-axis indicate the training block and VI, respectively. An asterisk indicates group differences in the VI ( $P < 0.05$ ). A shaded area represents 1 SEM. The delta value was computed by subtracting the values in the earlier blocks from those in later blocks. Note that the FB group but not the no-FB group showed higher values at the initial half of the training blocks, exhibiting the movement exploration. **I** The scatterplots of differential value of the VI between the blocks 1–2 and 19–20 (*x*-axis) relative to the differential value of keypress error (*y*-axis) in the FB and no-FB groups. Black and red lines were derived from a least-squares fitting in the FB and no-FB groups, respectively. There was a significant Pearson's correlation between the two variables in the FB group ( $P < 0.05$ ). Twenty-four right-handed skilled pianists participated in Experiment 2 (12 for each group).

individuals may benefit from other forms of sensorimotor training, such as practicing the individuated finger movements at the submaximal speed repetitively<sup>12</sup>, which suggests dependence of effective ways of improving this skill on the level of proficiency.

A puzzling observation of the present study was that the training targeting temporal feature of the keystrokes (i.e. timing) influenced spatial features of the motor skills, such as correct selection of the finger to be used during the sequential movements and movement exploration that was assessed based on the joint angular velocity. This can be related to previous results reporting that the ordinal sequence of movements is represented not independently from the temporal feature of movement sequence<sup>42,43</sup>. These results raise a possibility that training targeting the temporal feature of the sequential finger movements influenced control of the movement sequence, which however requires further investigation for uncovering this mechanism. For the training effect on the movement exploration, the present study assessed the movement exploration according to the peak rotational velocity of the finger joints. The timing of the keystroke depends not only on temporal features of the finger movements (e.g. timing of the peak rotational velocity), but also on spatial features of movements (e.g. magnitude of the peak rotational velocity)<sup>44</sup>. For instance, when the index finger hits the key earlier than the ring finger, it can occur with earlier timing and/or larger magnitude of the joint rotational velocity of the index finger compared with the ring finger. Because the temporal feature of the keystrokes is not independent of the spatial feature of the finger joint rotation, it is possible that the pianists modulated timing of the keystrokes during the decomposition training through exploring spatial features of the finger joint rotation. By contrast, because non-musicians are less skilled with respect to independent control of movements between the fingers compared with the pianists<sup>36,37</sup>, our finding suggests that non-musicians were not able to adjust the joint velocity even during the decomposed motor task requiring the individuated finger movements. A future study should be designed to shed light on mechanisms underlying the movement exploration.

In conclusion, the present study provides novel evidence that the decomposition of the complex motor skill in training with providing feedback of the timing error of synchronous multi-finger movements facilitates exploration of the finger movement pattern and thereby further improves the speed-accuracy tradeoff specifically for skilled pianists who had years of instrumental training. The lack of these improvements in the non-skilled pianists who underwent the skill decomposition training with error feedback, as well as in the skilled pianists who underwent each of the decomposition training without error feedback and conventional repetition training of the original complex task highlights that expertise reflects abilities of taking advantage of learning from the decomposition training with precise error information for further sophisticating the plateaued motor skill.

## Materials and methods

### Participants

Thirty-six right-handed skilled pianists (27 female) and 12 right-handed age-matched non-skilled pianists (10 female) participated in Experiment 1, and 24 right-handed skilled pianists (19 female) participated in Experiment

2. Skilled pianists in Experiments 1 and 2 were randomly assigned to 2 groups (12 per group) and to 2 groups (12 per group), respectively. These groups differed in ways of training, as described in the “Experiment 1” and “Experiment 2” sections. All 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. In particular, the skilled pianists won prizes at international piano competitions and/or underwent at least 10 years of piano training, whereas the non-skilled pianists had neither of these experiences. Exclusion criteria were a history of neurosurgery, movement and neuropsychiatric disorders such as focal dystonia, or metal or electronic implants inside the body. Informed consent was obtained from all participants prior to participation in the experiment. All experimental procedure was conducted by following the Declaration of Helsinki and was approved by the ethics committee of Sony Corporation. All ethical regulations relevant to human research participants were followed. To eliminate any potential effects of auditory and visual FB on motor performance and training, the digital piano was muted, and the participants were asked not to observe their fingers during the experiments, but to keep watching a screen in front of them.

### Measurement of piano movements

We used a digital piano with wooden keys in which MIDI sensors were implemented (VPC1 KAWAI Co.) in the two experiments. The movement timing and velocity of keypresses and key-releases were sampled at 1000 Hz using a custom-made program (LabVIEW, National Instruments Inc.).

### Measurement of finger movements

To assess kinematics of the finger movements, we recorded the time course of the finger joint angles by using a data glove with sensors surrounding the individual finger joints (CyberGlove III, CyberGlove Systems Inc.) in Experiment 2. We recorded the motions at 8 degrees of freedom with angular resolution  $<0.5^\circ$ , at 8.3 ms intervals (i.e., sampling frequency = 120 Hz). The measured angles were the MCP and PIP joint angles of the four fingers.

### Experiment 1

Thirty-six skilled pianists and 12 non-skilled pianists participated in Experiment 1. Experiment 1 consisted of a succession of pretest, training, and posttest sessions.

In the pretest and posttest sessions, the experimental task required the alternate repetition of two movement patterns that involve synchronous strikes of the two keys 20 times, using the right index and ring fingers for one movement pattern (movement pattern A) and the right middle and little fingers for another movement pattern (movement pattern B) (Fig. 1 A). When the keypresses were performed in an incorrect order/fingering (e.g., pressing the keys with the index and little fingers instead of the middle and little fingers for the movement pattern B), those keypresses were not counted as the successful 20 repetitions, and that trial was considered as an error trial. Prior to the pretest session, the participants repeated the experimental task 20 times to determine a movement tempo at which the number of error trials was approximately 6 out of 10 trials, and they were instructed to

maintain the movement tempo throughout the experiment. Each of the pretest and posttest sessions consisted of 10 trials. To confirm the ceiling effect of the repetition training of the complex motor skill, the 12 skilled pianists repeated the experimental task 30 times (i.e., 20 synchronous strikes  $\times$  30 times = 600 times) without any visual FB and took a 3-min break every 5 times.

In the training session, 12 skilled and 12 non-skilled pianists were allocated to the FB group (skilled and non-skilled FB groups). The participants in the FB group performed each movement pattern individually (i.e., either movement patterns A or B) but not their alternate repetition. In the training of the movement pattern A, the participants were asked to keep two keys with the middle and little fingers depressed prior to performing the task. After an auditory cue was provided (2000 Hz, 200 ms), they were asked to press two keys with the index and ring fingers together with releasing two keys with the middle and little fingers synchronously (i.e., movement pattern A). After the combination of the keypresses and key releases, participants received visual FB on the timing of these four finger motions. The FB displayed the onset of these keypress and key-release events with the four fingers within a time window of 0–100 ms. If the difference in the timing between the earliest and latest events of the key motions (i.e., timing error) was lower than 10 ms or larger than 20 ms, the circle corresponding to each finger on the display turned black or blue, respectively; otherwise, it turned red. The participants were instructed to minimize the timing error based on the two types of the visual FB. The training of the movement pattern B was conducted in the same manner as the training for the movement pattern A. In addition, 12 skilled pianists underwent training of each movement pattern separately without providing any visual FB about the timing error of movement synchrony between the fingers in order to identify the learning effect of training with the visual FB of the subtle timing error information on experts' expertise (no-FB group). The participants in the no-FB group were instructed to minimize the timing error of the finger movements based only on the somatosensory information derived from the motion and touches. The training sessions consisted of 600 trials (30 trials  $\times$  10 blocks  $\times$  2 movement patterns) in the FB and no-FB groups. The participants took a 5-minute break every 5 blocks. A half of them practiced the movement pattern A first and then practiced the pattern B. The other participants practiced the movement patterns in the reverse order.

## Experiment 2

Twenty-four skilled pianists participated in Experiment 2 and were randomly assigned to the FB group ( $n = 12$ ) and the no-FB group ( $n = 12$ ). Experiment 2 also consisted of a succession of pretest, training, and posttest sessions, although a paradigm of Experiment 2 was modified based on the results of Experiment 1.

Some participants from the skilled FB groups in Experiment 1 showed no error trial after the training, displaying the floor effect. Moreover, Experiment 1 was designed to train movement patterns A and B, whereas the movement exploration was changed specifically in movement pattern B. To further enhance the motor performance, we adjusted the experimental task and training in Experiment 2. First, participants were instructed to explore a movement tempo that resulted in approximately 8 error trials out of 10 trials prior to the pretest session, indicating the increased difficulty in the experimental task for Experiment 2 compared to Experiment 1. Second, Experiment 2 was designed to train only the movement pattern B. Thus, both the FB and no-FB groups underwent a training session consisting of 600 trials (30 trials  $\times$  20 blocks), with participants taking a 5-min break every 5 blocks. Third, in Experiment 1, we evaluated changes in the movement exploration using information on pressing and releasing velocities of the piano keys. In Experiment 2, to further assess these changes from actual finger joint movements, we used a data glove and assessed the movement exploration using the angular velocity.

## Data analysis

We calculated the number of the error trials in 10 trials as the index of the probability of the error occurrence in both the pretest and posttest sessions

(keypress error). The timing error of the keystrokes was calculated as the difference in the timing between the earliest and latest events of the key motions.

In Experiment 2, we calculated the rotational velocity of each finger joint to examine whether the exploration of finger joint movements occurred. First, we resampled the finger joint angles from each trial of the training session to 1000 Hz, which were then preprocessed with low-pass filtering (the second-order Butterworth filter with a cutoff of 10 Hz). Second, we extracted data from 100 ms before the first key-motion to 100 ms after the last key-motion. Third, we resampled these finger joint angles to 1000 samples to match the length across trials of the training session. Fourth, we calculated an absolute value of the angular velocity at each finger joint, and then calculated the mean absolute value between 8 finger joints and assessed the timing of the peak velocity. Finally, at the timing of the peak velocity, we extracted the signed angular velocity of each of the 8 finger joints (i.e. 8 values for each trial, in which the positive and negative value indicates the extension and flexion, respectively). To evaluate the amount of exploration of the finger joint movements during the training session, we calculated average values of extracted angular velocity of each of eight finger joints for each block. This average value is a vector that contains 8 elements for each block in the training session (i.e., 20 vectors). Then, we calculated a Euclidean distance in these vectors between all possible pairs of the two successive blocks (i.e., 19 Euclidean distances).

## Statistics and reproducibility

We used a linear mixed effects model (LME) or generalized LME (GLME) implemented in the lmerTest package in R. Our model included the factors appropriate for the data among the group, session (or block), and movement pattern as fixed effects along with their interactions. Individual variability was assessed by including participants and interactions between participants and within-factors (when the number of within factors is 2 or more) as random factors. For the timing error, the value of this variable at block 1 was included as a covariate to account for the difference between groups. To determine the significance of the fixed effects, Type II Wald chi-squared tests were performed using the Anova function in R with the car package. Multiple comparisons were performed using the emmeans package in R. Degrees of freedom of such comparisons were calculated using the Kenward-Rogge method, while *P* values were adjusted using the Holm method. We tested replicability of the results of experiment 1 through experiment 2 with different participants.

## Data availability

The data that support the findings of this study are available in the Supplementary Data 1. All other data are available from the authors on reasonable request.

## Code availability

The codes necessary for depicting the figures are available in the Supplementary Data 1.

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## Author contributions

Y.K. participated in the conception, organization, and design of the study, collected and analyzed the data, designed and ran the statistical analyses, and wrote the first draft and revised the manuscript. M.H. and S.F. helped to conceptualize and design the study, interpreted the data, and revised the manuscript. All authors reviewed and critiqued the draft and approved the final manuscript.

## Competing interests

The authors declare no competing interests.

### Additional information

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**Correspondence** and requests for materials should be addressed to Yudai Kimoto.

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