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Effects of altered sensory feedback on piano performance errors: An exploratory study

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Abstract
Music performance is an intensive sensorimotor task that involves the generation of mental representations of musical information that are actively accessed, maintained, and manipulated according to the demands of the performance. Internal representations and external information interact through feedback and feedforward processes that adjust the musician's motor behavior to optimize a musical performance. This study aimed to examine the relationship between altered sensory feedback and performance errors. Seventeen experienced pianists aged between 33 and 54 years performed Hanon Exercise N°1 from memory under four different conditions: (1) normal (normal sensory feedback); (2) closed fallboard (altered haptic and auditory feedback); (3) blindfolded (altered visual feedback); and (4) combined (blindfolded and closed fallboard; altered haptic, auditory, and visual feedback). Performance errors were quantified based on a video analysis of the performances. Results indicated that compared with normal performance, participants made significantly more note errors in the blindfolded condition and more bar-adding errors per trial in the closed fallboard condition. The comparison between the normal condition and the three altered sensory feedback conditions revealed the impact of altering sensory feedback in musical performance. These findings are discussed in the context of music learning.

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music, music imagery, performance errors, piano performance, sensory feedback

Introduction

Musical performance requires precise spatiotemporal control of sequential movements. The repetition of complex motor sequences creates working memory traces that are encoded and stored in long-term memory (Boutin & Doyon, 2020; Chen et al., 2020). These mental representations guide motor planning during performance, allowing the memory traces to be translated into coordinated movements (Gabrielsson, 2003). During the musical performance, musicians must monitor the perceptual outcomes of their actions, to detect errors and update their motor plans in real time (Cohen & Bodner, 2019; Helding, 2020; Hodges & Thaut, 2019). Indeed, musicians receive a multitude of concurrent sensory information during performance. This includes auditory, visual, and kinesthetic feedback, which enable them to monitor and control aspects of music performance, such as expressive timing, dynamics, articulation, and pitch accuracy (Bishop et al., 2013; Gabrielsson, 2003; Pfordresher & Beasley, 2014; Wöllner & Williamon, 2007).

During a musical performance, sensorimotor feedback and feedforward processes interact to determine the final motor output. Sensorimotor feedback is related to the control or modification of a process based on its effects. For example, a heavy action on a piano will cause a performer to use more force when depressing keys. Sensorimotor feedforward mechanisms represent the modification or control of a process based on the anticipation of its results (Wolpert et al., 2003). In other words, feedforward mechanisms are predictive processes based on internal models before sensory feedback is available. Internal models are developed over time based on learning and experience. An efferent copy of the motor command can be used to make predictions about an action's result based on the current situation. The feedforward information can then be compared with the predicted outcome. When the predicted outcome is unwanted, motor adjustments can be initiated to modify the predicted outcome so that it is closer to the desired result (Wolpert et al., 2003). In other words, musicians imagine the external outcomes they wish to achieve during performance. This triggers motor system predictions to best reach the desired outcome so that possible errors can be corrected (Altenmüller & Furuya, 2016; Bach et al., 2022; Oldrati et al., 2021); musicians anticipate the effects of their movements during performance (Bishop et al., 2013).

To make rapid predictions and perform precise movements, the internal models rely on proprioceptive and sensory feedback. In addition to the feedforward and feedback mechanisms, the construction of mental performance imagery also relies on working memory to access, maintain, and manipulate the musical information in accordance with performance requirements (Keller, 2012). Interestingly, the processing of pitch in working memory can be influenced by musical training. Musicians tend to be better able to process pitch information in working memory compared with nonmusicians (Weaver, 2015). With years of practice and listening experience, musicians develop expectations about the effects of their actions during performance and generate experience-dependent representations that are shared between sensory and motor systems (Keller, 2012; Keller & Koch, 2008; Pfordresher & Palmer, 2006). During performance, a musician compares the sensory information received as a result of the action (e.g., the sound produced) with their predicted outcome, allowing them to adjust their movements to produce the sound they want to hear (Bishop & Goebl, 2017; Penhune, 2019).

Given the importance of sensory feedback during performance, deliberately modifying sensory feedback—whether tactile, auditory, or visual—could emphasize its pivotal role in performance. More importantly, by manipulating sensory feedback, we can explore how feedback is compared with mental imagery of the performance because the sensory feedback is compared with the preestablished internal models, enabling real-time adjustments in musical performance. The role of auditory feedback in music performance has been extensively examined by altering or completely removing the sounds that result from playing a musical instrument (Nunes-Silva et al., 2021; Pfordresher & Palmer, 2002). In these studies, auditory feedback has been modified by muting the instrument's sound (Cheng et al., 2013; Finney, 1997; Pfordresher et al., 2014), using headphones to prevent the musician from hearing the mechanical attacks of the keys (Wöllner & Williamon, 2007), introducing delays in the auditory feedback (Cheng et al., 2013; Pfordresher et al., 2014; Ruiz et al., 2011), adding sequential shifts (where the auditory feedback is shifted to the previous or subsequent key in the sequence) or pitch fluctuations (where the pitch of the note is random and unpredictable) (Pfordresher et al., 2014). Research suggests that removing or altering auditory feedback unrelated to the planned motor sequence during the performance of a well-rehearsed and memorized piano piece does not seem to disrupt the performance of experienced musicians (Finney, 1997; Finney & Palmer, 2003; Pfordresher, 2005, 2008; Repp, 1999). But other types of altered auditory feedback do affect performance, such as when the auditory sensory feedback is delayed (Finney, 1997; Pfordresher & Palmer, 2002) or when mismatches between actions and pitch events are experimentally introduced (Couchman et al., 2012; Furuya & Soechting, 2010; Pfordresher & Palmer, 2006). These types of altered auditory feedback slow production rate, reduce pitch accuracy, and increase timing variability.

This pattern of results suggests that altered auditory feedback interferes with motor planning because movements are preceded by anticipating their perceived consequences (Hommel et al., 2001; Keller, 2012; Shin et al., 2010). Research suggests that anticipatory imagery enables action planning and expressivity in music performance by compensating for the missing or unreliable information. For example, pianists are able to replicate their intended dynamics and articulation in the absence of auditory feedback (Banton, 1995; Bishop et al., 2012, 2013, 2014). This notion is further corroborated by findings demonstrating the role of auditory–motor associations acquired through learning and experience (Bangert & Altenmüller, 2003; Bishop et al., 2013; Brown & Palmer, 2012; Highben & Palmer, 2004; Lappe et al., 2018; Madeira & dos Santos, 2022; Pfordresher & Chow, 2019). Studies generally indicate that experienced musicians have stronger shared auditory–motor representations (Bishop & Goebl, 2017; Keller & Koch, 2008; Pfordresher & Chow, 2019) and better musical imagery ability compared with novice or nonmusicians (Bishop et al., 2013; Brown & Palmer, 2012; Highben & Palmer, 2004).

Importantly, musical imagery is not limited to auditory imagery, but emerges as a product of the interaction of different sensory modalities (Brown & Palmer, 2013). Although auditory events constitute the "perceptual goal" of music performance, auditory information is not the only source of feedback in music performance (Pfordresher & Beasley, 2014). Indeed, visual and somatosensory (tactile and kinesthetic) information plays an important role in the successful production of complex action sequences (Goebl & Palmer, 2008; Kulpa & Pfordresher, 2013; Maidhof et al., 2013; Wöllner & Williamon, 2007). Moreover, musical imagery is thought to be a multimodal process by which musicians are able to anticipate the auditory features of musical sounds as well as the visual, proprioceptive, kinesthetic, and tactile properties of their musical-related movements (Keller, 2012). Unfortunately, little is known about the effect of altered visual or somatosensory feedback on music performance.

Visual information from either the piano keys or the musical score is important for many musical tasks, from sight-reading, to navigating intricate passages of disjunct movement, to the performance of a newly learned piece. One of the earliest studies examining the effect of visual feedback deprivation during sight-reading reported that pianists made more errors when they could not see their hands, whereas the absence of auditory feedback did not influence performance (Banton, 1995). Visual feedback also plays an important role during the learning of new musical sequences (Eldridge et al., 2010; Engel et al., 2012; Hasegawa et al., 2004; Kulpa & Pfordresher, 2013). For instance, Eldridge et al. (2010) examined the effect of visual feedback on nonmusicians' ability to learn a piano piece by ear. One group learned "normally," that is, they received full audiovisual feedback. A second group learned the piece but could not see their hands, that is, the visual feedback was inhibited. Participants who learned without visual feedback had greater difficulty matching the acoustic pitch to the corresponding piano key, suggesting poorer key-to-tone retention and highlighting the importance of multiple forms of sensory feedback during music learning in nonmusicians.

The impact of altering sensory feedback in expert musicians is poorly understood. Wöllner and Williamon (2007) compared the performance of eight skilled pianists in a task whereby they had to tap out the beat of an imagined piano performance, while trying to replicate the timing and intensity profile of the imagined piece in their tapping. Participants received normal feedback, or altered visual, auditory, or tactile feedback. Interestingly, the findings revealed that the absence of visual feedback (i.e., musicians playing with their eyes closed) had no impact on the consistency of expressive performance profiles, much like the effects observed with auditory feedback removal (i.e., playing on a muted digital piano with headphones to minimize the mechanical sounds of the piano). The authors suggested that these results are likely due to musical imagery, as it enables musicians to plan an action and anticipate its outcome even before a movement is executed or perceived.

While reduced auditory and visual feedback seemed to have minimal impact on expert musicians, Wöllner and Williamon (2007) found that the removal of kinesthetic feedback resulted in performance impairments of expressivity and dynamics. Kinesthetic information along with tactile information makes up the haptic system. These haptic subsystems use sensory information derived from built-in mechanical receptors in the skin (i.e., tactile inputs) as well as receptors embedded in muscles, tendons, and joints (i.e., kinesthetic inputs) (Lederman & Klatzky, 2009). Haptic feedback can, therefore, be altered by changing the point of contact for the fingers or their movement (i.e., feeling the resistance of the piano key being pressed down). In the Wöllner and Williamon (2007) study, for instance, kinesthetic feedback was altered by having participants tap a single piano key while imagining a normal performance of that piece. It remains uncertain how comparable the performances generated under distinct feedback conditions in this experiment are. Nevertheless, the importance of haptic feedback has been demonstrated in previous research with finger-tapping tasks, suggesting that finger-key contact is particularly relevant for timing accuracy (Aschersleben, 2002; Goebl & Palmer, 2008; Repp, 1999). However, to the best of our knowledge, no other studies have examined the effect of the alteration of kinesthetic and tactile feedback on music performance.

The purpose of this study was to examine how expert musical performance is affected by disrupting sensory feedback. Specifically, we manipulated visual, auditory, and haptic feedback during performance to investigate how altered feedback affects musical performance. We hypothesized that, if musical imagery involves an updated mental representation based on feedback processes, altered feedback would significantly disrupt performance of a well-rehearsed piece by increasing performance errors. Specifically, based on our literature review, we predicted that simply blindfolding the participants, in isolation, should not significantly

Figure 1. Example of the First 6 Bars of Hanon Exercise 1, Provided as a Reference for Readers.

affect their performance. However, we hypothesized that altered haptic feedback—by having pianists play on the fallboard—would have a more pronounced impact. Furthermore, we anticipated that when both visual and haptic feedback were altered concurrently, performance may be significantly worse. This was based on the expectation of interactions between sensory modalities, which play a crucial role in the process of making predictions in music imagery.

Materials and methods

Participants

Participants were recruited from local music conservatories. The final sample included 17 professional pianists (10 women), aged between 33 and 54 years ($M = 41.5$, $SD = 7.41$), with a range of 20 to 49 years of musical study ($M = 33.59$, $SD = 8.01$). Participants had an average of 2.3 hr of daily musical practice ($SD = 1.9$, range: 1–8), 21.4 hr of average music listening per week ($SD = 11.2$, range: 5–40), and began formal music lessons by an average age of 7.2 years old ($SD = 3.1$, range: 3–16). All participants were right-handed, had no history of neurological diseases, and had no visual or hearing impairments. The study was approved by the Ethics board of the State University of Minas Gerais (CAAE 10610319.0.0000.5525) and all participants provided informed consent to take part.

Stimuli and equipment

For this study, we used Exercise N°1 of The Virtuoso Pianist (Hanon, 1911). This piano exercise is performed bimanually and consists of a pattern of finger movement that is repeated in an ascending and then descending order, covering a span of four octaves. The regular rhythmic pattern is composed of 16th notes in 2/4 time. The exercise requires the sequential use of fingers 1 to 5 in the right hand and then 5 to 1 in the left hand, repeatedly until Bar 14. From Bars 15 to 29, the finger sequence is reversed (5–1 for the right hand and 1–5 for the left hand). Bar 29 has a ritornello for Bar 1. There is a closing bar after the repeat (Bar 30), which contains a half note played with Finger 1 in the right hand and Finger 5 in the left hand. This piece was chosen because it is a well-known exercise, allowing participants to perform it from memory. It had a repetitive rhythmic structure that favors a more controlled action sequence. This was an intentional choice as we were not interested in evaluating musical dynamics or musicians' expressive intentions in this study. Figure 1 shows the first six bars of the piano exercise.

Participants played the exercise on a Yamaha Studio C3 Grand Piano. Video cameras were positioned on the left side of the piano—focusing on the pianist's hands—and behind the pianist from the right side. One of the cameras used was a 4K action camera with Wi-Fi compatibility, and the second point camera was a Canon model PowerShot SX510 HS. The videos were recorded in 1440 × 1080p resolution at 30 frames per second and 48 kHz 256 kbps stereo audio. In the experimental conditions where participants were blindfolded, a sleep mask was used to guarantee 100% blackout for external lighting and to ensure that they did not have any visual information. This mask was used in previous studies (e.g., Dieter et al., 2014).

Study design and procedures

Participants were informed a week before the study that they would perform the Hanon Exercise N°1 and were instructed to practice the piece at 80 bpm. Before the experimental procedure, participants practiced with the metronome to become familiar with the tempo; however, the metronome was not used during the experiment.

After completing written informed consent, participants performed the piano piece by memory at an approximate tempo of 80 bpm in four experimental conditions. During normal performance (C1), participants played as usual on the piano keyboard and had normal access to sensory feedback. In the fallboard performance (C2), participants played with the piano fallboard closed, hence having limited auditory feedback and altered haptic sensation (i.e., although they could feel their fingers touch the fallboard, there was no haptic feedback from the resistance of the piano key). The blindfolded condition (C3) limited participants' visual information from the piano keyboard or the positioning of their hands, while haptic and auditory information was present. Finally, in the last condition (C4), participants played on the closed fallboard and were blindfolded, hence limiting visual, auditory, and haptic sensory feedback.

The study had six blocks. In each block, participants performed C1 (normal) followed by one of the other conditions (C2, C3, or C4). That way, C1 was repeated 6 times while Conditions C2, C3, and C4 were each completed twice. The order of the altered conditions was counterbalanced between participants.

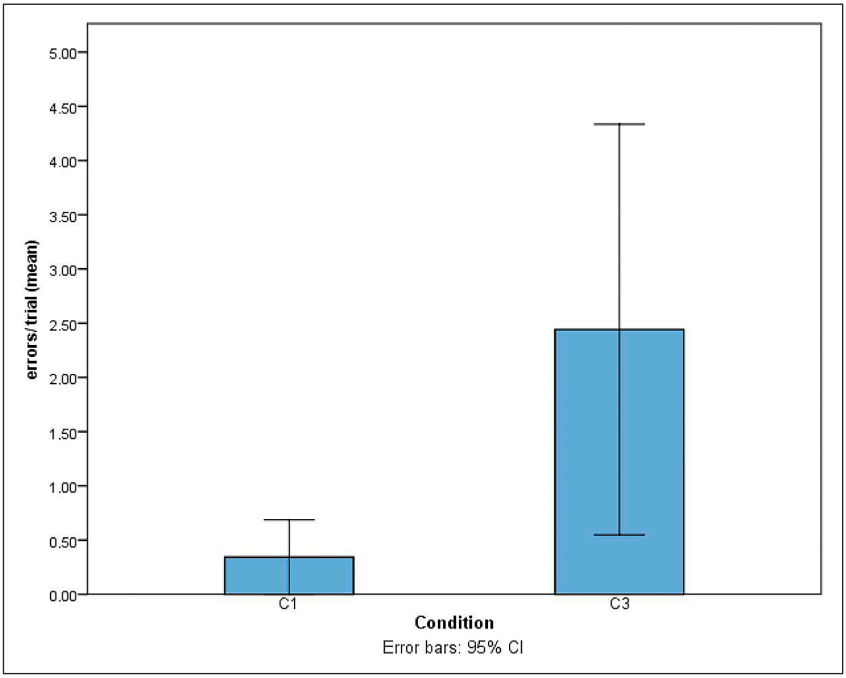
Data analysis

Performance errors in each condition were computed from video analysis by independent raters. In the conditions without audio information, the analysis of the errors was performed by observing the fingering of the participants in the videos. Errors were classified into four types:

1. Note errors: occurred when the participant executed other notes that were not written in the score in a certain part of the exercise (i.e., played the wrong note or moved the wrong finger; added a note or finger movement, missed a note or finger movement).
2. Bar-adding errors: occurred when the participant played more bars than were written in the score.
3. Bar subtraction errors: occurred when the participant played fewer bars than were written in the score.
4. Rhythmic errors: occurred when the participant failed to perform the note or finger movement at the correct time. No rhythmic errors were observed in any condition, and will not be reported further.

The proportion of errors in each trial was used for the analyses; the total number of errors for each condition was then divided by the total number of trials in each condition. Note errors were quantified only for Conditions C1 (normal) and C3 (blindfolded) because it was not possible to extract the data in conditions where there was no auditory information because the piano keys were not pressed. To determine the error rate, the total number of errors in Conditions C1

Figure 2. Note Errors per Trial for Conditions C1 (Normal) and C3 (Blindfold) ($n = 17$).



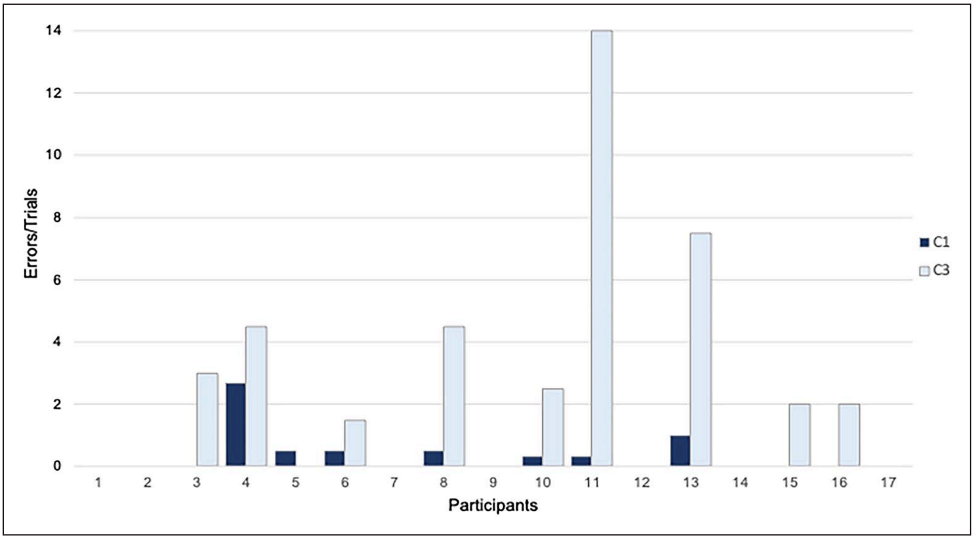
and C3 was divided by the number of trials (six and two, respectively) in each participant ($n = 17$). Tests of normality indicated that data distributions in the different conditions were predominantly leptokurtic and positively skewed, tending toward lower scores with indices greater than one for both kurtosis and skewness (Blanca et al., 2013; Foster, 1986). Furthermore, the results of both the Kolmogorov–Smirnov (KS) and Shapiro–Wilk tests supported the findings from the kurtosis and skewness analyses, indicating that the number of errors per trial in all conditions did not follow a normal distribution ($p < .001$). Given the deviations from normality, we used the repeated measures Friedman test and Wilcoxon signed rank test to compare the numbers of errors between conditions. Following the Friedman test, we conducted post hoc pairwise comparisons with a Bonferroni correction for multiple comparisons to identify the pairwise groupings that differ significantly. We also performed Spearman's rank correlations to explore if there was an association between the number of errors and demographic variables, including age, years of musical study, hours of daily musical study, and the age at which musical training began. These correlations were calculated to understand how individual differences affected performance in the study. All analyses were conducted using SPSS (PASW Statistics 18) software.

Results

Note errors

A Wilcoxon signed rank test was conducted to compare error rates between conditions. Overall, as shown in Figure 2, there were more note errors in the blindfolded condition (C3) ($M = 2.4$, $SD = 3.68$) compared with the control performance (C1) ($M = 0.3$, $SD = 0.6$), and this difference

Figure 3. Note Errors per Trial for Each Participant, Across Conditions C1 and C3.



was statistically significant ($z = -2.703$, $p = .007$, $n = 17$). The 95% confidence interval for the effect size in C1 ranged from 0.001 to 0.685, while for C3, it ranged from 0.548 to 4.334.

In Figure 3, note errors for Conditions C1 and C3 are plotted separately for each participant ($n = 17$). Overall, there were fewer note errors in C1 across all participants. Second, there was much higher between-subject variability in the blindfolded condition (C3), with some participants performing with very high accuracy, whereas others made many more errors compared with C1. A one-way analysis of variance (ANOVA) test was conducted to check whether note errors in both conditions differed significantly from zero, with results indicating that mean values in C1 did not differ from zero, $t\,(16) = 2.123$, $p = .05$, $n = 17$, whereas results were statistically significant in C3, $t\,(16) = 2.733$, $p = .015$, $n = 17$.

Bar-adding errors

To examine differences in performance between all four conditions, the Friedman test was conducted. For bar-adding errors (Figure 4), the analysis revealed a significant difference between conditions, $\chi^2(3) = 19.846$, $p < .001$, $n = 17$. Post hoc pairwise comparisons with Bonferroni correction for multiple comparisons indicated a statistically significant difference between C1 and C2 ($p = .02$) as well as between C2 and C3 ($p = .04$). Participants made more errors in the altered haptic and auditory condition (C2; $M = 1.70$, $SD = 2.35$) than in the normal feedback condition (C1; $M = 0.0$, $SD = 0.0$) and the blindfolded condition (C3; $M = 0.5$, $SD = 0.24$), respectively. The pairwise comparisons with C4 (blindfolded and closed fallboard) were no longer significant following Bonferroni correction for the p values. Figure 4 shows the mean error per trial for the participants ($n = 17$) in all four conditions. Error bars represent 95% confidence intervals, ranging from 0.496 to 2.915 for C2, −0.066 to 0.184 for C3, and 0.264 to 2.501 for C4.

Overall, there were more bar-adding errors and greater intersubject variability in the error rate in Conditions C2 and C4 when the piano fallboard was closed (Figure 5). Interestingly, participants had shown no bar-adding errors per trial when performance was normal (C1).

Figure 4. Bar-Adding Errors per Trial for All Conditions (C1 = Normal; C2 = Fallboard: C3 = Blindfold; C4 = Fallboard & Blindfold) (n = 17).

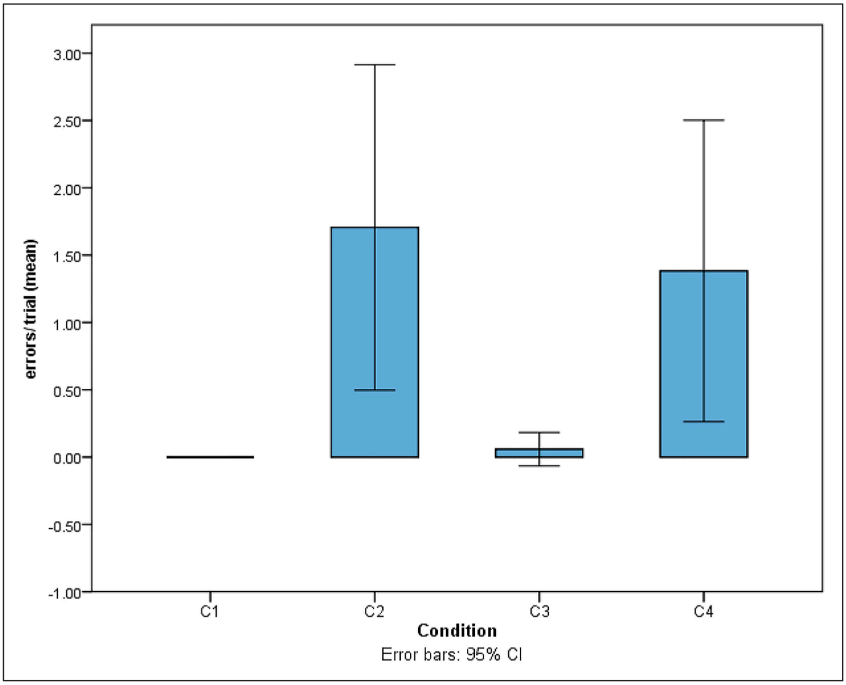


Figure 5. Bar-Adding Errors per Trial for Each Participant, Across All Conditions (C1 = Normal; C2 = Fallboard: C3 = Blindfold; C4 = Fallboard & Blindfold).

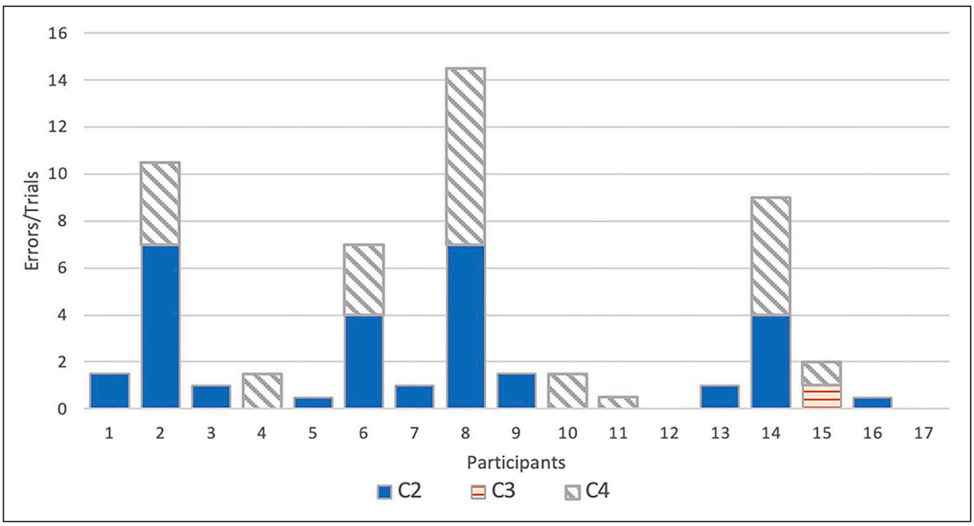
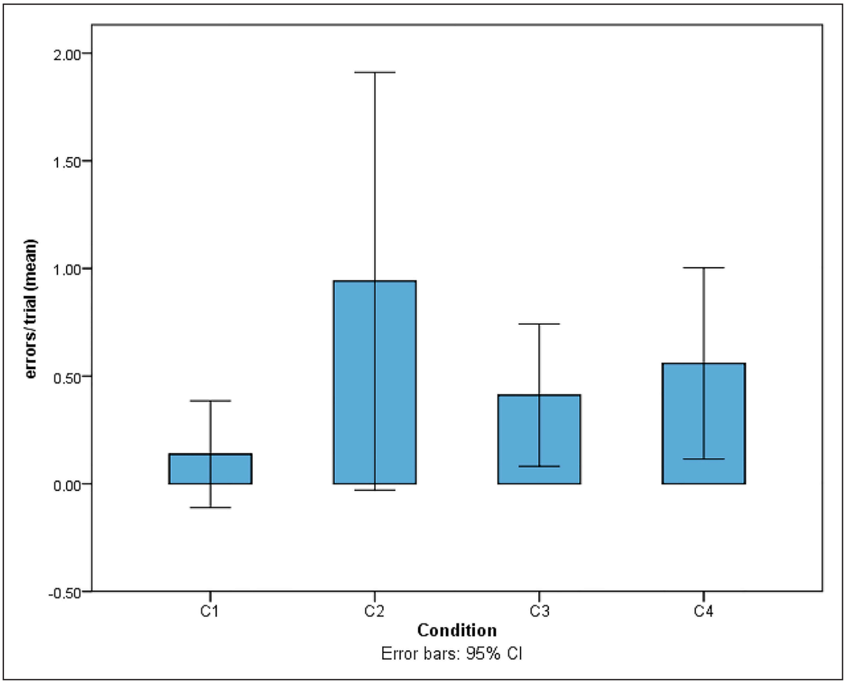


Figure 6. Bar-Subtraction Errors per Trial for All Conditions (C1 = Normal; C2 = Fallboard: C3 = Blindfold; C4 = Fallboard & Blindfold) ($n = 17$).



Bar subtraction errors

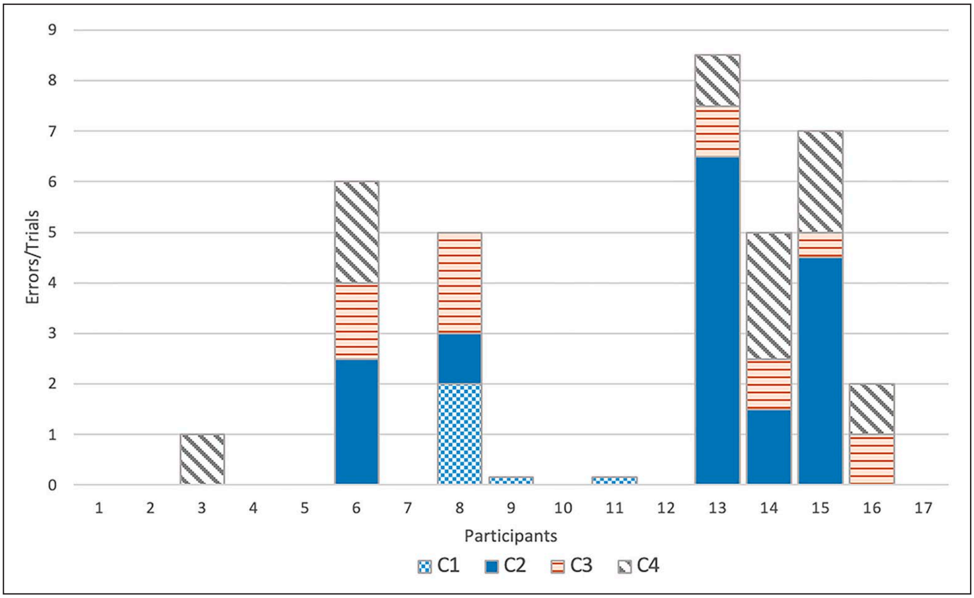
Bar subtraction errors were quantified using a Friedman test. Bar subtraction rates were similar across all conditions, $\chi^2(3) = 1.905$, $p = .592$, $n = 17$. Figure 6 shows the mean number of bar subtraction errors per trial across the four conditions. Error bars represent 95% confidence intervals, ranging from −0.111 to 0.386 for C1, −0.029 to 1.911 for C2, 0.081 to 0.742 for C3, and 0.115 to 1.003 for C4.

In Figure 7, subtraction errors are plotted separately for each participant ($n = 17$). Overall, there were very few subtraction errors (fewer than three per trial), except for Participants 13 and 15 in Condition C2. There was also more variability between the participants' performance errors for C2 condition.

Correlation analysis

Spearman's rank correlation analysis showed that there was a positive correlation between the number of note errors in the blindfolded condition (C3) and the age at which participants began their musical training, indicating a trend that participants who started training at a younger age had fewer note errors ($r_s = .539$, $p = .026$, $n = 17$). There was also a positive correlation between age and bar-adding errors ($r_s = .685$, $p = .002$, $n = 17$) and age and bar subtraction errors ($r_s = .529$, $p = .029$, $n = 17$) in the fallboard condition (C2). The number of bar-adding errors was also positively correlated with years of music training in the fallboard condition (C2) ($r_s = .691$, $p = .002$, $n = 17$).

Figure 7. Bar-Subtraction Errors per Trial for Each Participant, Across All Conditions (C1 = Normal; C2 = Fallboard: C3 = Blindfold; C4 = Fallboard & Blindfold).



Discussion

This study investigated the impact of altered visual, auditory, and haptic feedback on performance errors during piano performance. Participants made more errors when the sensory feedback was altered compared with a typical musical performance, emphasizing the importance of external perceptual feedback during performance.

Specifically, there was an increase in note errors when no visual feedback was available (C3) compared with the normal performance condition (C1). This finding is inconsistent with previous work, which has shown that the removal of visual feedback has little impact on the performance of experienced pianists (Wöllner & Williamon, 2007). This may be due to greater variability in our participants' performance when blindfolded (C3). Interestingly, the correlational analyses suggested that this finding could be associated with the age at which the participants started their musical training, with earlier music training onset being related to fewer note errors when blindfolded. This finding is consistent with the idea that earlier musical training is associated with greater musical skills in adulthood (Wesseldijk et al., 2021). Moreover, experienced musicians perform better when replicating an established internal performance model rather than merely focusing on executing the required movements (Bishop & Goebl, 2017). It is therefore possible that musicians with earlier onset of training had more robust internal models of the piece, which led to fewer errors.

We also observed an increase in bar-adding errors when haptic and auditory feedback was limited. Interestingly, the alteration or removal of haptic and auditory feedback had a more detrimental effect on performance than the lack of visual feedback. This suggests that auditory and haptic feedback plays a crucial role in monitoring the outcome of one's actions. Without this information, performers rely solely on the mental representation of the piece being executed, and thus performance suffers. Here, we demonstrate that haptic feedback is likely more important for performance compared with visual feedback.

The ability to store, access, and manipulate mental representations of musical information is necessary for the construction of mental musical images. Auditory and sensorimotor feedback is crucial for music image construction. This feedback is compared with mental imagery (predictions) during performance which allows for real-time verification of the performance. The feedback can also be used to modify future actions and internal models so the real performance matches the expectations held in the mental image (Keller, 2012). The absence of this feedback could explain the bar-adding errors observed when there was altered auditory and haptic feedback (C2) because participants were not able to verify if the mental image corresponded satisfactorily with their performance. It is also important to consider that the inherent repetitiveness of Hanon exercises may be a factor in the occurrence of bar-adding errors. The repeated rhythmic pattern may have made it difficult for participants to accurately track where they were in the score, thereby resulting in additional bars. Future research with different musical materials could help untangle this issue.

Wöllner and Williamon (2007) highlighted the importance of the mental representations during musical performances. When removing sensory feedback, musicians create mental representations to "fill in" for the feedback that was altered or removed (Wöllner & Williamon, 2007). Accordingly, the development of mental representations should be viewed as a vital stage in musical learning because these internal representations remain stable in many different performance situations. This study differs from Wöllner and Williamon's (2007) experiment because they asked participants to perform a chosen piece by tapping on a single piano key, whereas here participants played the entire piece on the piano fallboard. The fallboard conditions changed the haptic feedback context by altering both tactile and kinesthetic afferent subsystems of the haptic system, changing the point of contact and the movement of the fingers. Although pianists could feel their fingers on the fallboard, they were unable to receive the tactile stimulation from pressing a piano key. In addition, the playing surface was higher in the fallboard conditions, which may have changed the forearm angle used by pianists during performance. The method from Wöllner and Williamon (2007) preserves the feeling of the touch of the keyboard; however, it limits the movement of fingers, hands, and arms of the pianist necessary to perform the whole internal model stored in their memory.

In this study, when individuals received altered haptic feedback and normal visual feedback (C2), their proportion of bar-adding errors was higher than that in normal performance (C1). Surprisingly, this did not occur when participants had no visual feedback combined with altered haptic feedback (C4). One possible explanation for this pattern of findings is that when a participant was blindfolded, they were better able to focus on the mental imagery of the piece. Alternatively, seeing their fingers over the fallboard (C2) may have resulted in distorted visual feedback because the pianist normally expects to see their fingers over the keys of the piano. Thus, visual feedback could become a distraction that hinders the musician's performance, particularly when other forms of sensory feedback are manipulated. It remains possible that only a subset of participants experienced difficulty in generating predictive feedforward information from the internal models when they could see their fingers while playing on the piano fallboard as there was higher intersubject variability in these conditions.

When the fallboard was closed and haptic and auditory feedback was altered (C2), the number of bar-adding errors was positively correlated with the age of the participant and the number of years of music training. Similar to the group analysis, one possible explanation for this relationship is that the visual feedback may have been a distraction for the participants. Older and more highly trained musicians may have been more susceptible to this feedback alteration due to having more years of training and music experience. They may be less flexible in terms of adapting to unusual performance circumstances (Pfordresher & Chow, 2019), whereas less experienced musicians are still learning and regularly engage in performance techniques that are novel to them.

One critical observation in this study was the variability between the participants, indicating that altered feedback affected individuals differently. Some participants were more affected by visual deprivation and others by auditory deprivation and altered haptic feedback. The individual differences observed could be linked to the diversity of musical skills in the participants, including technical skills, playing by ear, or mental representation consolidation. As Highben and Palmer (2004) have suggested, there is scarce literature on interparticipant variability, given that most studies focus on group averages. It is interesting to note that even highly experienced musicians are highly variable in their performances when using only mental representations to perform. According to Sloboda (2000), these individual differences between performances are complex and multidimensional. Our study highlights how this variability manifests when sensory feedback during the performance is altered. Nevertheless, individual characteristics potentially linked to these differences were not directly investigated in this study, and exploring this aspect further could be a valuable avenue for future research.

Overall, no rhythm errors were observed in any of the conditions. The Hanon exercise is rhythmically simple for pianists because it is composed only of 16th notes except for a half note at the end. The chosen piano exercise focuses on building a motor memory so that it is possible to play simple rhythms faster. Considering that all pianists in the study had an advanced level of training, they also had a well-established memory for the rhythmic pattern of the piece. For most musicians, when the fingers get used to the continuous rhythmic sequence, it becomes easy to reproduce, reducing the chances of errors (Anggoro & Karyawanto, 2020). In this study, Hanon Exercise N°1 provided little opportunity for metric or rhythmic errors, as it is a repeated pattern of semiquavers. This limitation made the study less sensitive to metric and rhythmic errors that might have been present if we had used a more complex piece. In future work with more complex pieces, a metronome could be used to control the tempo and to identify if visual or tactile feedback affects tempo, rhythm, or metric errors.

The comparison between music performance in normal and altered conditions allows for the observation of how changes in performance environment affect musical performance. Under altered conditions, there is a need for motor remapping and changes in cognitive schemata previously consolidated through learning, which may be associated with the neural mechanisms underlying adaptation to changes imposed by the environment (Pfordresher & Chow, 2019). Increased knowledge of how altering specific sensory modalities leads to performance errors would be helpful in understanding how the sensory-perceptual system affects music performance. Our results reinforce the idea that musical performance depends on the relationship between internal models and sensory information available during performance. In this sense, altering the context of the performance influences the internal model. Thus, the cognitive schemata previously consolidated through learning have to be adapted to the new context. In addition, while our study aimed to restrict sensory feedback in musical performance by removing visual, auditory, and normal haptic inputs, we acknowledge that the inclusion of additional conditions, such as employing a keyboard with mute capabilities or utilizing a mute graphic fingerboard, holds promise for further exploring the intricate relationship between sensory feedback and musical performance. Future investigations could delve deeper into the effects of these stricter limits on sensory feedback, potentially shedding more light on the interaction between musical performance, mental representation, and sensory feedback.

This study also has implications for music education. Understanding the different types of sensory feedback and how they may be used to improve musical performance is crucial for creating learning strategies. Sensory feedback—including auditory, visual, and haptic feedback—provides learners with essential information that can guide their performance, helping them to optimize their practice time and improve their overall musical abilities. Auditory and visual feedback can be stimulated when recording oneself playing and listening back to identify areas that need improvement and by watching recordings of accomplished musicians performing the same piece to evaluate their performance (Nunes-Silva et al., 2021; Riley et al., 2005). When playing the piano, haptic feedback is essential for timing finger movements and can be enhanced by the sensory data obtained at the point of contact between the finger and the key (Goebl & Palmer, 2008).

Consolidating mental images is critical for identifying and correcting errors during performance, especially in the absence of sensory feedback. Deliberate mental practice can develop these auditory, visual, or haptic mental representations (Wöllner & Williamon, 2007). More consolidated mental images can be developed by learning associations between movements involved in playing an instrument and the resulting auditory effects (Keller, 2012). Studies have also shown that it is easier to learn the ideal motor sequence for music performance after training focused on visual–motor aspects of musical performance, compared with training focused only on auditory–motor aspects of musical performance (Engel et al., 2012). Overall, incorporating strategies to develop mental representation highlights the critical role of sensory feedback in music performance, and could lead to more effective and efficient music learning. Furthermore, while consolidating mental images is vital to music performance, we also need to consider individual variability and contextual differences when developing optimized music learning methods (Odendaal, 2019).

The relationship between musical training, mental representations, and the capacity to adapt preexisting cognitive schemata to new environmental configurations should be further explored. This study highlights that the alteration of sensory feedback can affect musical performance. Because performance errors varied according to the alteration of different sensory modalities, it is likely that they originated from the interaction of altered feedback and the internal representation of the musical piece. Improving our understanding of how the interaction between feedback and feedforward mechanisms influences internal models of musical performance will contribute to a deeper comprehension of musical performance and the establishment of strategies to improve musical learning.

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