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Impacts of diversified repetition on multilevel motor organization during piano performance

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Abstract. This study investigates the effects of diversified repetition practice on pianists' bimanual coordination by comparing performances before and after a practice session involving variations in rhythm, articulation, dynamics, and tempo. Two pianists, identified as P1 and P2, participated in the study by performing the F major pentatonic scale across three phases: pre-test, practice, and post-test. Audiovisual recordings, MIDI data, and motion capture data were used to analyze the movements of fingers, wrists, and elbows. Three aspects of performance were examined: note onset asynchrony (temporal synchronization), preparatory gesture amplitude (motor planning), and key attack velocity (dynamics). Motor strategies in proximal segments were also observed, focusing on patterns of symmetry, phase, and amplitude. The results revealed distinct responses between participants and across different note combinations. In some cases, increased simultaneity and gestural reorganization were observed; in others, there was a reinforcement of pre-existing patterns. The findings suggest that diversified repetition may promote subtle adjustments, motor stabilization, and the intensification of already established motor strategies. It is concluded that its effects arise from the interaction between technical and motor factors, and that its application is most effective when tailored to the specific needs of each performer.
Keywords. Diversified repetition, Bimanual synchronization, Motor coordination, Motion capture, Piano performance

Título. Impactos da Repetição Diversificada na Organização Motora Multinível Durante a Performance Pianística

Resumo. Este estudo investiga os efeitos da prática com repetição diversificada na coordenação bimanual de pianistas, por meio da comparação entre execuções realizadas antes e depois de uma sessão de estudo com variações de ritmo, articulação, dinâmica e andamento. Dois pianistas, identificados como P1 e P2, participaram da pesquisa, executando a escala pentatônica de Fá maior em três fases: pré-teste, prática e pós-teste. Foram utilizados registros audiovisuais, dados MIDI e dados de captura de movimento, que permitiram analisar os gestos de dedos, punhos e cotovelos. Três dimensões da performance foram examinadas: assincronia entre os onsets das notas (sincronização temporal), amplitude do gesto preparatório (planejamento motor) e velocidade de ataque das teclas (dinâmica). Também foram observadas estratégias motoras nos segmentos proximais, com foco em padrões de simetria, fase e amplitude. Os resultados revelaram respostas distintas entre os participantes e entre as diferentes combinações de notas. Em alguns trechos, observou-se maior simultaneidade e reorganização gestual; em outros, a manutenção ou intensificação de padrões expressivos preexistentes. Os achados indicam que a repetição diversificada pode promover ajustes sutis, estabilização motora e reforço de estratégias motoras já consolidadas. Concluiu-se que seus efeitos decorrem da interação entre aspectos técnicos e motores, sendo sua aplicação mais eficaz quando adaptada às necessidades específicas de cada intérprete.
Palavras-chave. Repetição Diversificada, Sincronização Bimanual, Coordenação Motora, Captura de Movimento, Performance Pianística

Introduction

Hand synchronization is a core skill in piano performance, demanding highly precise temporal coordination to align finger movements with musical structures (Goebl & Palmer, 2013). This precision depends on specialized neural and biomechanical mechanisms and reflects the broader motor complexity of piano playing (Goebl, Sebastian & Widmer, 2010; Swinnen & Wenderoth, 2004). Jabusch (2006) emphasizes that keyboard performance requires exceptional spatiotemporal accuracy. Achieving such coordination calls for interhemispheric integration and sustained practice aimed at refining motor control and expressive fluency (Furuya & Altenmüller, 2013; Ito et al., 2023).

Beyond the biomechanical and neural complexity of piano playing, the human tendency to synchronize with rhythmic stimuli reflects a broader biological principle. While synchronization often appears as a default mode of the central nervous system (Kelso, 2012), skilled musical actions frequently necessitate overcoming this automatic tendency, thereby revealing profound neural plasticity. This is particularly relevant considering the two distinct timing modes proposed by Repp and Su (2013): a pulse-based, efficient mode and a duration-based mode. The latter, which is effortful and cerebellum-dependent, becomes crucial when no clear external beat is present. For solo pianists, where precise hand coordination hinges on an internal sense of timing rather than external cues like a metronome, this duration-based mechanism is paramount. Yet, this intricate intrapersonal synchronization – the precise internal coordination of independent yet co-dependent motor actions – remains underexplored in the literature.

Repp (2006) summarizes research on synchronization with rhythmic sequences, addressing three contexts: simple movements with complex sequences, complex movements with simple sequences, and both being complex. However, it does not examine hand synchronization in the absence of an external pulse. Repp and Su (2013) also note that topics such as self-paced rhythm and intrapersonal coordination fall outside the scope of their reviews.

Repetition is among the most widely employed strategies in musical learning, spanning both individual (Barry, 1992, 2007; Rohwer & Polk, 2006; Mantovani & Dos Santos, 2022; Monteiro & Dos Santos, 2023) and collective practices (Corbalán et al., 2019).

Yet, despite its recognized role in gesture automation and refinement (Repp, 2005), the subtle micro-adjustments that accompany the process and their significance for motor learning remain largely overlooked in current research.

Building on Monteiro (2022), who categorized repetition types and noted that excessive insistence may hinder hand synchronization, this study explores how diversified repetition impacts synchronization in the absence of external rhythmic cues. The prevalence of stabilization-focused strategies reveals a gap concerning the role of intentional variation in practice, particularly in temporal coordination.

Aims

This study aimed to investigate the effects of diversified repetition on pianists' bimanual coordination by comparing performances recorded before and after practice. Specifically, we sought to: (i) examine how practicing the F major pentatonic scale with variations in rhythm, tempo, articulation, and dynamics influences temporal synchronization between the hands; (ii) identify individualized coordination patterns that emerge or persist after practice; (iii) assess changes in attack intensity and accuracy based on MIDI-derived velocity and onset data; and (iv) analyze variations in gestural preparation—particularly in the movements of fingers, wrists, and elbows—captured via motion tracking, in order to explore the relationship between spatial-motor organization and timing accuracy.

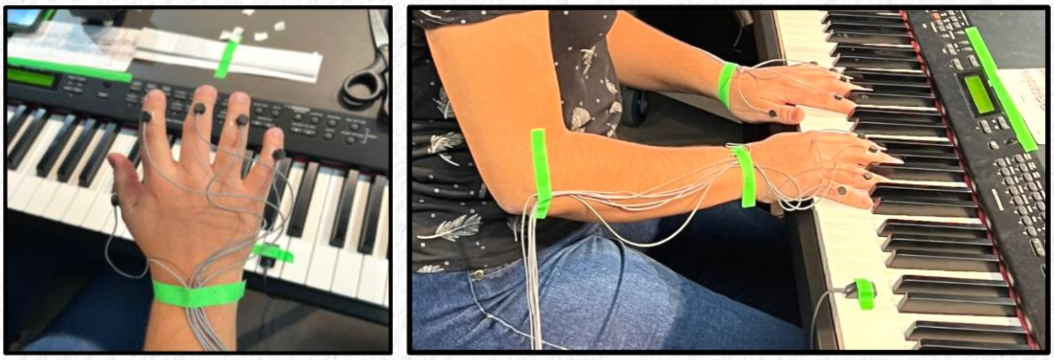
Method

In this exploratory quasi-experimental study, two right-handed expert pianists performed the F major pentatonic scale in a protocol with three stages: pre-test, practice, and post-test. The analysis focused on three conditions: (a) single notes played simultaneously by both hands, (b) ascending movements between the hands, and (c) a specific keyboard register, with the left hand in octave 3 and the right hand in octave 4. In the pre-test, each pianist played 12 consecutive repetitions; during practice, they applied diversified repetition strategies (variations in rhythm, tempo, articulation, dynamics, separate-hand practice, and block practice); and in the post-test, they repeated the initial task 12 times for comparison.

The F major pentatonic scale was chosen as a simple and manageable task that nonetheless involves a minimal technical challenge due to a skipped note. This design allowed examination of the immediate impacts of diversified repetition in a controlled setting and provided a basic framework that facilitates subsequent studies with musical excerpts.Data collection was performed using three resources simultaneously: MIDI data, the Polhemus motion capture system, and audiovisual recordings. MIDI (Musical Instrument Digital Interface) data were obtained from a digital piano connected to a computer via a MIDI interface, using Reaper software to record performances.

For motion capture, the Polhemus LIBERTY system was used, with 16 channels, which allows precise and continuous tracking at high speed (240 Hz per sensor), without the need for line of sight. The system recorded the gestures of the upper limbs in three aspects through an electromagnetic field (Figure 1), using 15 sensors positioned on the medial phalanges of each finger (10), on the wrists (2), on the elbows (2), and on the piano (1). Audiovisual recordings were used as complementary support.

Figure 1: Polhemus sensor configuration on the right hand of P2 (left) and on both upper limbs during performance (right)



Source: The authors

Data Processing

Data processing was a challenging step, carried out collaboratively by the research team, and required specific strategies to deal with the multimodal nature of the recordings.

The analysis was conducted in the MATLAB environment, using scripts[1] developed exclusively for this investigation.

To assess bimanual synchronization, an algorithm was used that calculates the asynchrony between the onsets of notes extracted from MIDI files. The script identifies the attack time of each note and determines, in simultaneous events, which hand pressed the key first, allowing an objective estimate of the temporal deviations between the hands.

The amplitude of the preparatory gesture was analyzed using motion capture data and a custom script that quantified vertical finger displacement immediately before key attack. The process combined automated analysis with visual inspection of motion graphs to ensure accuracy. The gesture was defined from the lowest vertical point before the upward motion to the highest point just before note onset.

The attack intensity (velocity) was extracted from MIDI files using Sonic Visualiser and categorized by note combination and hand, allowing for performance comparison.

For each of the three aspects—onset asynchrony, gestural amplitude, and velocity—12 repetitions were analyzed in the pre-practice phase and 12 in the post-practice phase. Data were grouped by note combination and hand, with arithmetic mean and standard deviation calculated for each condition. Graphs created in Excel visually highlighted the intervention's effects on various performance parameters.

The paired t-test was used to statistically verify differences between conditions, with a significance level set at $p < 0.05$. Preliminary results indicate that P1 and P2 responded differently to practice with diversified repetition, revealing different patterns of adaptation and motor exploration.

Results and Discussion

Analysis of bimanual synchronization of the F major pentatonic scale

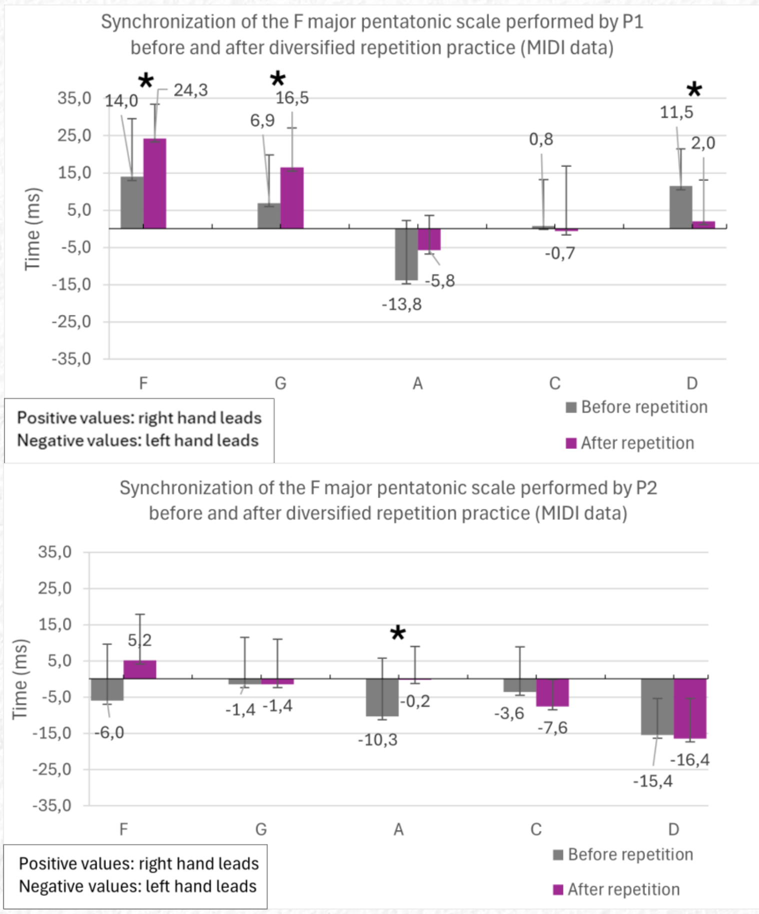
Bimanual attack synchronization was analyzed based on the temporal differences between note onsets, extracted from the MIDI data. The graphs presented in Figure 2 show the average values of asynchrony between P1 and P2 hands during the execution of the F major pentatonic scale, comparing the moments before and after practice with diversified

[1] The scripts used for data analysis are available at: https://github.com/palomafmonteiro

repetition. Positive values indicate right-hand anticipation, while negative values correspond to left-hand anticipation. Columns marked with asterisks indicate statistically significant differences between the conditions ($p < 0.05$).

For P1, the results revealed considerable variability between the note combinations. In the pre-test, right-hand anticipation was observed in four of the five combinations (F, G, C, and D), with emphasis on F (14.0 ms) and D (11.5 ms). After practice, the effects were distinct: there was an increase in the time lag in F and G (both with statistical significance) and an improvement in synchronization in D (reduction to 2.0 ms, also significant). Combinations A and C maintained values close to simultaneity in both conditions, without statistically relevant changes. These results suggest that diversified repetition led to specific motor reorganizations, improving synchronization in one note combinations while increasing time lags in other two, likely due to varying technical and biomechanical demands.

Figure 2 – Synchronization before and after practice – F major pentatonic scale (P1 and P2)



Source: The authors

In P2's case, the data indicated a predominance of left-hand anticipation in all combinations, both before and after practice. Only the A combination showed a statistically significant improvement, with a reduction in asynchrony from -10.3ms to -0.2ms, approaching simultaneity. In the other combinations, the changes were subtle and not significant.

Interestingly, this was the only note played with the same finger in both hands, suggesting that using homologous fingers may enhance temporal stability. Future studies could test this by comparing parallel and contrary motion scales.

The asynchrony data reinforce the importance of considering the individual characteristics of the performance, since in some notes there was an approximation to simultaneity, while in others an increase in the time lag was observed. These findings highlight the need for a localized analysis of the effects of varied practice, the musical excerpt and considering each pianist's motor performance and biomechanical strategies.

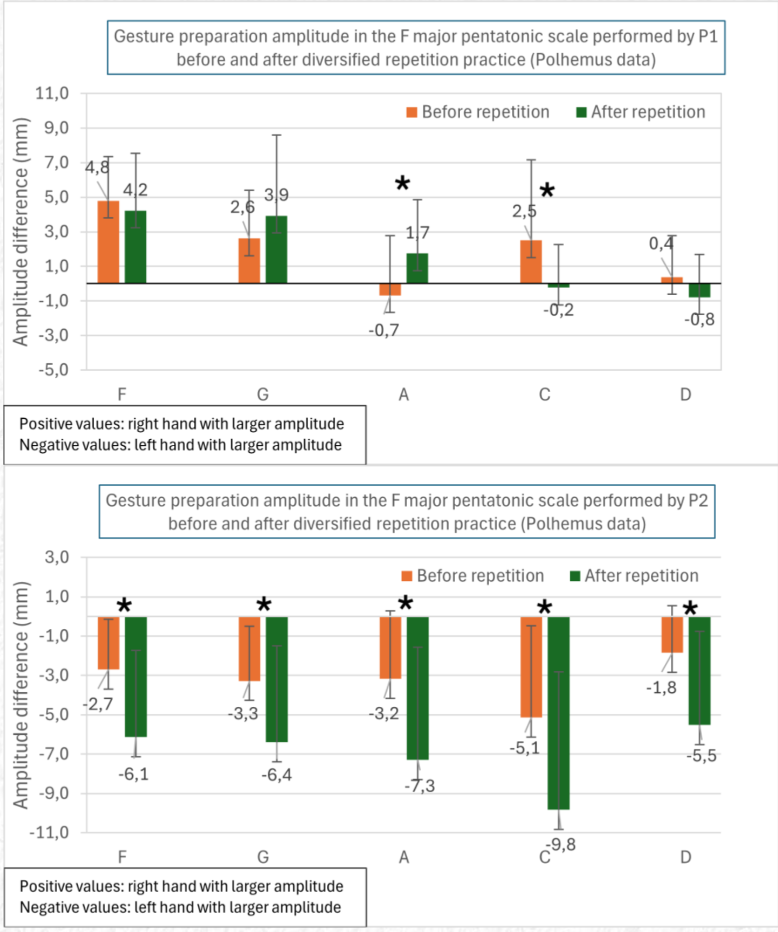
Analysis of the amplitude of gestural preparation in the F major pentatonic scale

The analysis of the data on the amplitude of gestural preparation, obtained through motion capture data, revealed contrasting responses between the two pianists after practice with varied repetition. The differences between the hands were expressed in terms of the average amplitude of the preparatory gesture, with the sign of the values indicating the hand that performed the widest movement before the attack of the note. The graphs in Figure 3 illustrate the average difference in amplitude between the hands of P1 and P2 in each note of the F major pentatonic scale, comparing the pre- and post-practice moments. Positive values indicate larger amplitude of the right hand, negative values, of the left hand.

For P1, only the notes A and C showed statistically significant differences. Before the practice, the note A was preceded by larger preparation of the left hand, while the right hand showed larger gestural amplitude in the note C. After the intervention, these patterns were reversed. These changes suggest that the practice with diversified repetition promoted a localized gestural reorganization, with changes in the way both hands prepared for the attack in specific combinations.

Interestingly, the reorganization emerged precisely at the only small leap in the scale (A–C), suggesting that this local structural constraint increased motor demands, prompting an adaptive refinement of preparatory gestures. From a coordination dynamics perspective, such transitions may act as critical points that destabilize default patterns.

Figure 3 – Preparatory gesture amplitude (per finger) before and after practice – P1 and P2



Source: The authors

In contrast, P2 presented more consistent gestural behavior. Even before practice, the data indicated a predominance of larger amplitude in all combinations, with values ranging from -2.7 mm (F) to -5.1 mm (C), and relatively homogeneous differences. After practice, these discrepancies increased across all notes, with emphasis on C (-9.8 mm), A (-7.3 mm), and G (-6.4 mm). These results are consistent with Palmer's (2004) findings, which showed that peak movement amplitudes tend to increase as tempo accelerates. In P2's post-practice recording, the significantly faster tempo — resulting from the diversified repetition task — is accompanied by larger preparatory gestures, suggesting that increased movement amplitude may reflect motor adaptations implemented to maintain accuracy under higher temporal demands.

In general, the results indicate that the effects of diversified repetition on gestural preparation are not homogeneous and appear to depend on individual factors, the approach adopted during practice and the pre-existing motor organization of each pianist. In some cases, practice favored adjustments in gestural preparation between the hands; in others, it functioned as an agent of stabilization and reinforcement of previously consolidated motor strategies.

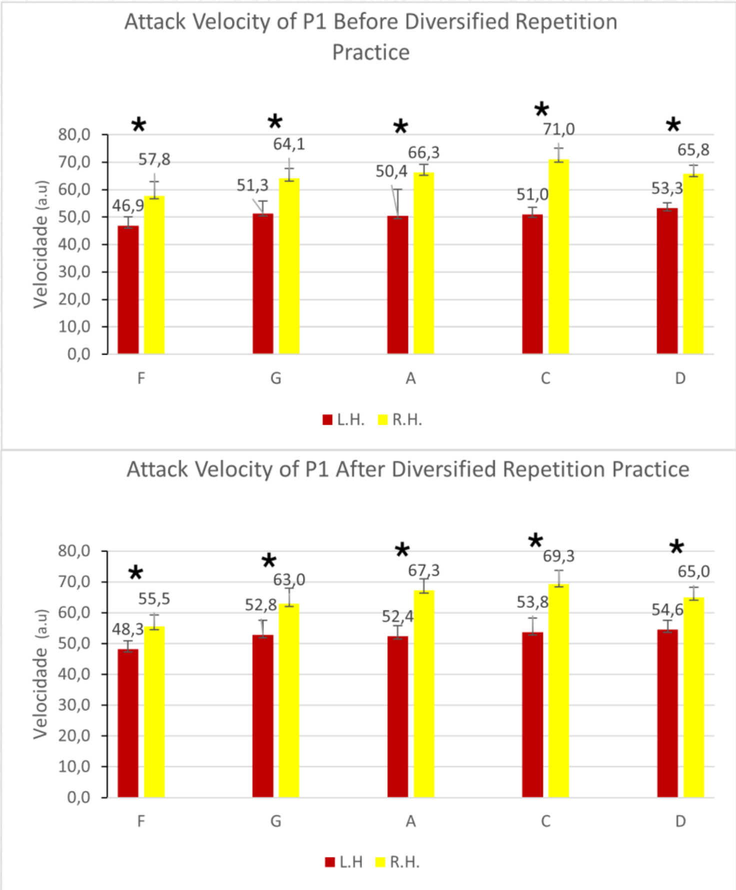
Attack Velocity Analysis of Notes - P1

Figure 4 illustrates the average velocity values, that is the force with which notes are struck when P1 plays the F major pentatonic scale, comparing the moments before and after practice with varied repetition. The red columns represent the data for the left hand, and the yellow ones for the right hand. In the MIDI protocol, velocity is a numerical measurement ranging from 0 to 127 in arbitrary units (a.u) corresponding to the intensity or force applied to the key: the higher the value, the greater the emphasis and the resulting sound volume. This measurement allows us to evaluate aspects of performance dynamics and potential differences in articulation between the hands.

P1's data showed that, in all five analyzed combinations, the velocity values were systematically higher in the right hand, with particular emphasis on note A (66.3 on the right and 50.4 on the left) and C (71.0 on the right and 51.0 on the left). This pattern may indicate a motor predominance of the right hand in dynamic production**,** though it could also reflect differences in hand function and biomechanical efficiency. The variability between repetitions, represented by the error bars, was relatively low, suggesting consistency in execution.

After diversified repetition practice, the pattern of higher velocity in the right hand was maintained, with statistically significant differences in all combinations, as indicated by the asterisks in the graphs. The largest disparities were again recorded in notes A (67.3 on the right and 52.4 on the left) and C (69.3 on the right and 53.8 on the left), reaffirming a consistent pattern of greater attack intensity by the right hand.

Figure 4 – P1 – Average velocity of notes before and after diversified repetition.



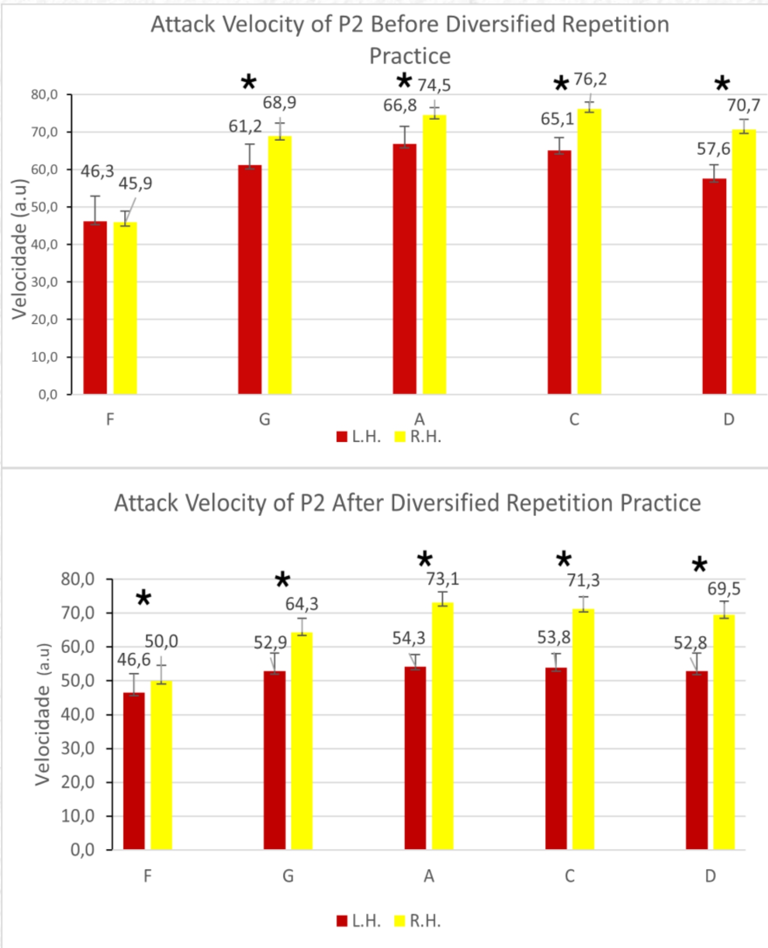
Source: The authors

Attack Velocity Analysis of Notes –P2

Looking at P2’s results (Figure 5) before practice, except for the F note, the right hand presented consistently higher values across all other notes, with statistically significant differences in the notes G, A, C, and D. The most pronounced contrasts occurred in the notes C (65.1 on the left and 76.2 on the right) and D (57.6 on the left and 70.7 on the right), indicating a clear pattern of greater attack intensity by the right hand. For the F note, the values were practically equivalent (46.3 on the left and 45.9 on the right), with no statistically significant difference.

After the diversified repetition practice, note F showed an increase in velocity, with the right hand now presenting significantly higher values than the left. This change introduced a new instance of right-hand predominance, which was already observed in all other note combinations and remained consistent after practice. Notably, the velocity values for the left hand decreased substantially across several notes, for example: from 66.8 to 54.3 in A, from 65.1 to 53.8 in C, and from 57.6 to 52.8 in D, while the right hand maintained relatively high values. The largest disparities continued to appear in notes C (53.8 left / 71.3 right), D (52.8 / 69.5), and A (54.3 / 73.1), reinforcing the persistent pattern of stronger articulation by the right hand. Although the right-hand velocities showed a slight decrease in absolute terms, the asymmetry between hands remained significant. These findings suggest that diversified repetition did not lead to a dynamic redistribution between hands but may have supported subtle refinements in attack force, particularly by reducing intensity in the left hand.

Figure 5 – P2 – Average velocity of notes before and after diversified repetition.



Source: The authors

The significant reduction in left-hand velocity after the diversified repetition practice may reflect a more economical and efficient motor strategy. Given the participant's right-hand manual dominance, the right hand maintained higher velocity values, likely due to greater control and coordination. In contrast, the left hand may have adapted its gesture to prioritize precision over intensity. This modulation could also suggest a reorganization of motor demands or an internalization of more efficient movement patterns as a result of the varied practice.

Analysis of wrist and elbow movement patterns – P1 and P2

General organization and analysis axes

This section analyzes the wrist and elbow movements of both participants based on motion capture data. Three main variables were considered: two linear (measured in centimeters) and one angular (measured in degrees). From a linear perspective, the variation in height (Z-axis) and anteroposterior displacement (X-axis) of the wrists and elbows were computed representing vertical (up and down) and horizontal (forward and backward toward the keyboard) motion, respectively. Positive and negative values indicate spatial position (to the left or right of the reference point) as defined by the motion capture system. From an angular perspective, the elevation angle (El) was measured, corresponding to flexion-extension movements of the wrists and elbows. An increase in angular values—whether positive or negative—corresponds to a larger flexion.

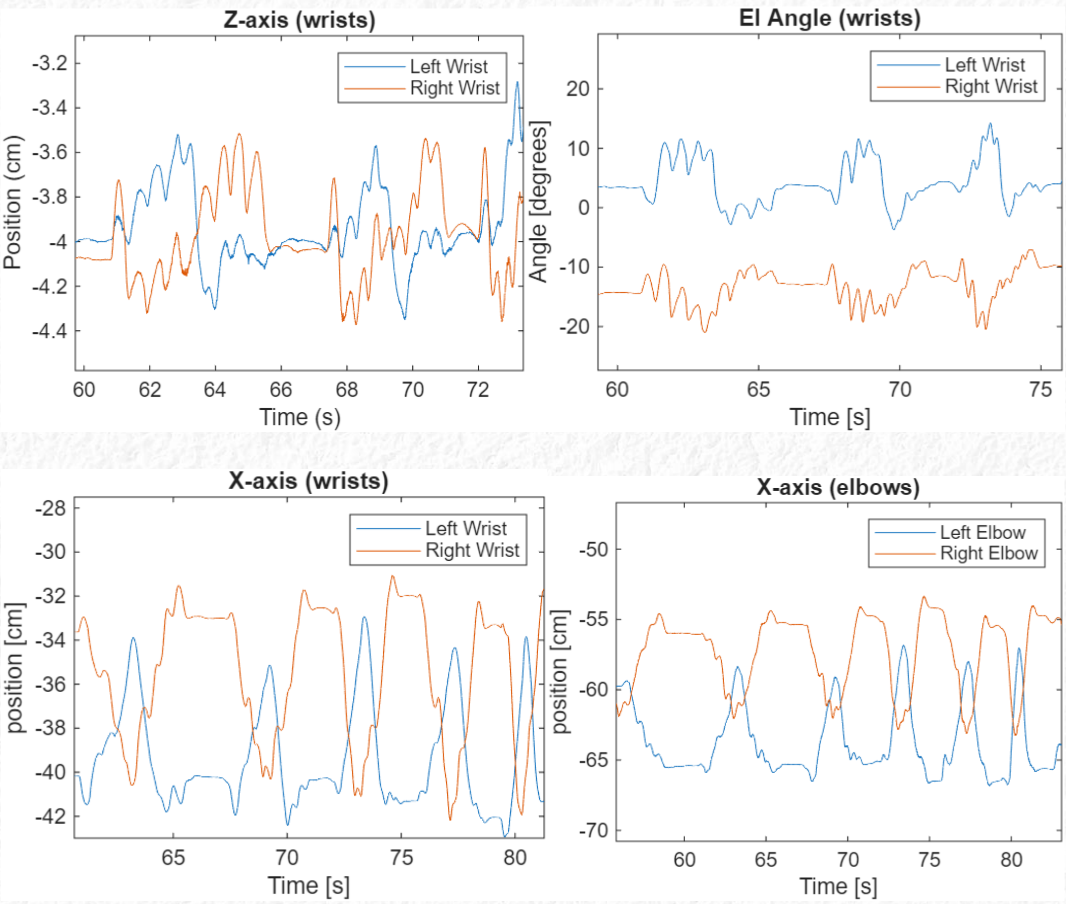
These parameters enable a more precise description of the spatial dynamics of gestures during performance, making it possible to identify patterns of symmetry, alternation, and compensation between the two sides of the body. The analysis presented refers only to the post-practice condition (with diversified repetition), as the observed patterns remained consistent across both phases (pre- and post-test), indicating the stability of each participant's gestural strategies.

Specific Strategies per Participant

P1 exhibited a gestural strategy characterized by alternation and intersegmental compensation (Figure 6). On the Z-axis, a recurring three-phase cycle was identified: similar height preparation of the wrists (in-phase preparation), opposite movement during scale execution (anti-phase execution), and a new similar height preparation at the end.

The El angle follows this pattern of oscillations in opposite directions, forming an alternating rhythmic dynamic. The X-axes of the wrists and elbows reinforce this alternation: when the segments on the left side move forward toward the keyboard, those on the right side move backward, and vice versa. This pattern is repeated cyclically throughout the performances, suggesting a coordinated motor control strategy distributed between the limbs.

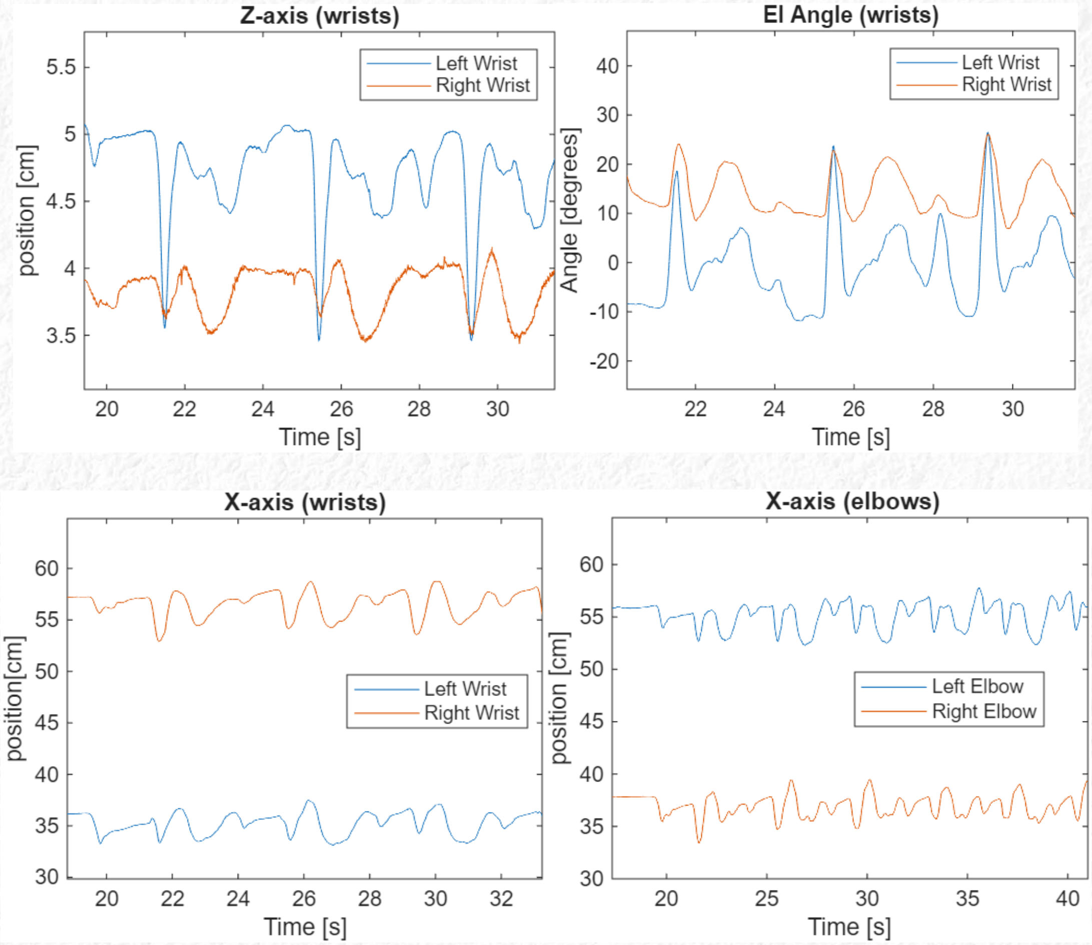
Figure 6 – P1 – Post-practice graphs of Z and El axes (wrist) and X axes (wrist and elbow), showing initial repetitions.



Source: The authors

In contrast, P2 demonstrated a symmetrical and synchronized gestural pattern (Figure 7). On the Z-axis and in the El angle of the wrists, the hands moved in phase throughout the 12 repetitions of the scale, with parallel trajectories and regular oscillations. The X-axis of the wrists and elbows confirms this symmetrical organization: both sides moved forward and backward simultaneously, with no signs of alternation or interlimb compensation. This pattern indicates a movement strategy in which all segments operate as a unified whole.

Figure 7– P2 – Post-practice graphs of Z and El axes (wrist) and X axes (wrist and elbow), showing initial repetitions.



Source: The authors

These contrasting profiles reveal different biomechanical strategies adopted in response to the same task. Participant P1 exhibited a distributed and alternating gestural pattern, which may favor greater independence between the hands, while P2 adopted a mirrored and simultaneous organization, potentially beneficial for overall motor control and energy efficiency.

In P1's case, hand movements followed an alternating (anti-phase) pattern: as one hand advanced toward the keyboard, the other retreated, aligning with the scale's fingering and likely reducing joint strain while optimizing reach. This strategy reflects a biomechanically efficient solution and aligns with Swinnen (2002) and Kelso's (1995) descriptions of interlimb anti-phase coordination, which, though less stable than in-phase, promotes greater limb independence and adaptive flexibility. P1's use of this mode suggests a functional response to both technical and motor demands in piano performance.

MIDI-derived asynchrony data (Figure 2) indicate that contralateral movements between body segments are associated with increased variability in inter-hand asynchrony, showing both improvements and increased desynchronization after practice. Such fluctuation may reflect an exploratory approach, favoring motor reorganization based on the specific demands of each note combination.

P1's velocity data (Figure 4) reveal consistently higher values in the right hand, both pre- and post-practice, suggesting right-hand predominance in dynamic production and possibly reflecting the alternation pattern and melodic prominence of the right hand. However, attack intensity results from a complex interplay of digital adjustments, motor strategies, and contributions from proximal segments like wrists and elbows — underscoring the need for further research into the multifactorial nature of pianistic gesture.

P2 exhibited a symmetrical, in-phase gestural pattern in wrists and elbows, consistent with the temporal stability seen in the asynchrony data (Figure 2). All note combinations showed consistent left-hand anticipation, with minimal change after practice. Only note A showed a statistically significant shift, approaching simultaneity. These results indicate that, despite a stable and unified strategy, P2 was able to make localized temporal refinements.

P2's velocity data (Figure 5) reveal consistently high values in the right hand, while the left hand showed a notable post-practice decrease in intensity. This dynamic adjustment suggests an effort to enhance precision and control, without altering the established gestural framework.

The convergence of spatial and temporal data is also reflected in P1's preparatory gesture amplitude (Figure 3), with changes like the inversion of dominance on notes A and C mirroring the motor reorganization seen in both asynchrony and intersegmental alternation. The anti-phase strategy seems to have promoted differentiated hand engagement, enabling more precise preparatory adjustments.

In P2, on the other hand, the maintenance of a symmetrical pattern among upper body segments coincides with the strengthening of already existing gestural amplitude patterns, particularly in the left hand, suggesting that practice with diversified repetition acted as a reinforcement of previously internalized strategies.

The integration of wrist and elbow movement data with asynchrony, gesture amplitude, and attack intensity analyses reveals those gestural strategies — whether alternating or symmetrical — are not merely biomechanical choices. Instead, they reflect integrated patterns shaped by the interplay between motor coordination, timing, and dynamic control. These strategies emerge from the interaction of spatial, temporal, and dynamic aspects of performance.

Conclusion

Diversified repetition revealed specific and nuanced effects on different aspects of piano performance. The integrated analysis of inter-hand synchronization, preparatory gestures, and attack intensity showed that the intervention's impact varied across note combinations and between participants, depending on their individual motor profiles. In some cases, practice led to increased simultaneity and localized motor reorganization; in others, it reinforced preexisting tendencies, enhancing gesture amplitude or dynamic adjustments.

These findings suggest that diversified repetition does not uniformly balance performance between the hands but instead promotes subtle adjustments, motor refinement, and the consolidation of motor strategies. Despite adopting contrasting gestural strategies, both performers achieved favorable outcomes shaped by their own motor organization. The ways in which each pianist moves, synchronizes, articulates, demonstrates that multiple physical pathways can support effective performance.

Future research should expand on these results by including a larger sample of participants, broader musical material, and medium- to long-term assessments, in order to deepen our understanding of how varied practice influences coordination, motor organization and motor learning in music performance.

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