Towards an Implicit Metric of Sensory-Motor Accuracy: Brain Responses to Auditory Prediction Errors in Pianists

Conference Paper · June 2023

DOI: 10.1145/3591196.3593340

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ABSTRACT

During listening to music, the brain expects specific acoustic events based on learned musical rules. During music performance expectancy is additionally created based on motor action by linking keypresses to their sounds. We investigated EEG (Electroencephalography) signals to auditory expectancy violations in piano performance and perception. In our study, pianists experienced manipulations of different acoustic features, such as pitch and loudness, during playing and listening to piano sequences. We found that manipulations during performance elicited deflections with stronger amplitudes compared to manipulations during perception indicating that the action of producing sounds strengthens auditory expectancy. Loudness manipulations, violating musical regularity, elicited deflections with smaller latencies compared to pitch manipulations, which violate harmonic expectancy, suggesting that the brain processes expectancy violations of distinct acoustic features in a different way. These EEG signatures may prove useful for applications in intelligent music interfaces by providing information about sensory-motor accuracy.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

Electroencephalography, Auditory Neuroscience, Music Neuroscience, Intelligent Music Interfaces

ACM Reference Format:
Elisabeth Pangratz, Francesco Chiossi, Steeven Villa, Klaus Gramann, and Lukas Gehrke. 2023. Towards an Implicit Metric of Sensory-Motor Accuracy: Brain Responses to Auditory Prediction Errors in Pianists. In *Creativity and Cognition (C&C '23), June 19–21, 2023, Virtual Event, USA.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3591196.3593340

C&C '23, June 19–21, 2023, Virtual Event, USA

ACM ISBN 979-8-4007-0180-1/23/06…$15.00
https://doi.org/10.1145/3591196.3593340

1 INTRODUCTION

Listening to music as well as playing a musical instrument is a favorite past time of many people. For a past time activity, it has several significant upsides: music plays a beneficial role in human development of various cognitive functions like language, logical thinking and memory as well as social behaviors [34]. Specifically, the active playing of a musical instrument activates a multitude of brain structures involved in cognitive, sensorimotor, and emotional processing which is likely to have beneficial effects on the psychological and physiological health of individuals [23].

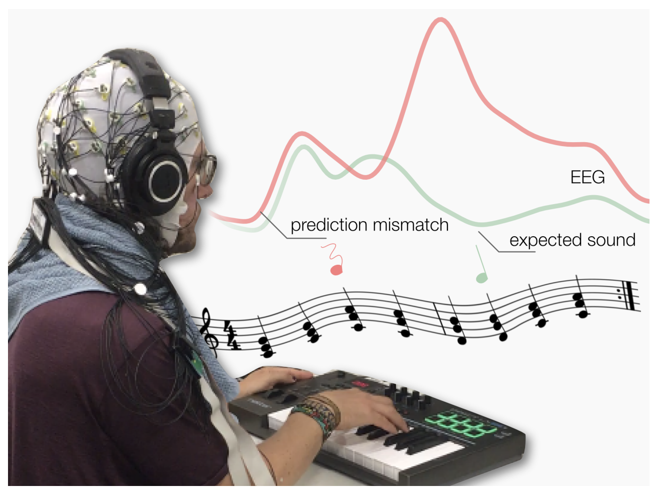

Figure 1: We compared brain responses of pianists to auditory feedback manipulations during playing and listening of piano sequences. To provoke participants to process an unexpected sound, we sometimes manipulated the sound output of a MIDI keyboard in various ways. We found differences in the brain response between predicted and unexpected sound feedback in both playing (see example in the figure) and listening to the piano.

Musical sound consists of complex structures and acoustic regularities. Basic components of music are pitch, timing, loudness, timbre, as well as higher-level elements like rhythm and harmony [37]. Through exposure to music as well as the production of music, the brain internalizes musical rules and learns to form predictions about sound based on harmony, timing, and regularity. Single tones within a musical sequence that fall out of the musical context, like having a different timbre, an out-of-key pitch, irregular loudness, or wrong timing, therefore violate auditory predictions formed by the brain [39].

In contrast to passively listening to music, actively playing an instrument involves complex motor processes that are tightly coupled with auditory processes to link acoustic events to respective movement patterns. By practicing playing music, the brain learns an internal representation of the instrument that maps motor patterns to auditory feedback and the other way round [1]. For example, when pressing a certain key on the keyboard with a certain force, a pianist expects immediate auditory feedback that has a specific pitch and loudness. This type of prediction is violated if the instrument produces a sound that does not match the finger movement. Such auditory prediction errors during perception or performance of music are known to elicit brain responses that can be measured with EEG (Electroencephalography) and analyzed with high temporal resolution, i.e., within a few hundred milliseconds after tone onset [38, 39].

In this paper, we compared the brain responses of pianists to auditory feedback manipulations during the playing and listening of piano sequences and, crucially, investigated how they vary for manipulations of different acoustic features. For this, EEG data of 7 experienced pianists were recorded while they played on a MIDI keyboard that occasionally manipulated the pitch and loudness of single tones. Pitch manipulations were designed such that the manipulated sound of a keypress sounded either harmonic or dissonant within the key of the currently played piano sequence. With velocity changes, in contrast, we analyzed the brain responses to small compared to large increases in loudness levels.

1.1 Towards an Implicit Metric of Sensory-Motor Accuracy of Musical Experiences using Event-Related Potentials

Our work was motivated by neuroadaptive technologies. These technologies make use of a probe, a stimulus presentation independently controlled by the system, for example, an irregular sound output. The idea then is that the user's brain responses to such probes can be used to extract and infer implicit information about the user [26]. Such responses can come in the form of specific features in the EEG, such as those arising when a user's prediction is violated [41]. In a previous work by Zander et al. [41], the authors demonstrated a brain-computer interface that observed the user's EEG response to random cursor movements. How severely the random dot movement violated the user's intention to move the cursor toward a specific goal location was directly reflected in the amplitude of event-related potentials (ERPs) in frontal electrodes providing a time-domain EEG feature for real-time adaptation due to its minimal computational overhead [4].

With this paper, we entertain the idea of obtaining personalized diagnostics about musical proficiency using brain measurements. More precisely, we envision a system that probes how practitioners' brains respond to irregular, faulty, system outputs during playing a MIDI piano using ERPs. Supplementing *objective*, i.e. MIDI-based, performance metrics, such brain responses could be derived into general parameters of *subjective* sensory-motor accuracy of musical experiences. Access to such general parameters would enable personalized training of musical experiences, tailored to the sensory-motor strength and challenges of the individual.

2 RELATED WORK

In the following, we provide an overview of different ERP components related to prediction errors during auditory processing and summarize previous work on which ERP components are differentially involved in piano performance and auditory perception of piano sequences.

2.1 ERPs of Auditory Prediction Errors during Music Perception

Harmonic prediction errors and the violation of acoustic regularities like loudness, tuning, or timbre are found to be reflected in different ERP components. Physical deviance from acoustic regularities is generally related to an ERP component called the mismatch negativity (MMN), which is a fronto-central negative potential with a latency of 150–250 ms [30]. In contrast, harmonic predictions built on learned musical rules are related to the early right anterior negativity (ERAN), lateralized to the right brain hemisphere, or the bilateral early anterior negativity (EAN). These components appear in the same time window as the MMN from 150 to 250 msec after the stimulus but are observed in anterior regions of the scalp [22]. As EAN and ERAN relate to harmonic syntax in music, they have also been denoted as music-syntactic MMN [25].

Koelsch et al. [24] conducted an ERP study with 18 nonmusicians who listened to chord sequences that infrequently contained chords that violated harmonic expectancy. In their study, dissonant sounding Neapolitan chords with two out-of-key notes were used to replace chords in different places in short piano sequences. Manipulated chords elicited an ERAN with an onset at around 150 msec. They further showed that with increasing degree of harmonic expectancy violation the ERAN showed larger deflections with shorter latencies and a clearer lateralization. Lastly, they investigated the effect of probability of violation and observed larger amplitudes if unexpected chords appeared less frequently [24].

Another study by Leino et al. [27] designed a similar experiment with 10 non-musicians listening to chord sequences that contained Neapolitan chords in different positions with notes outside the prevailing key to violate the rules of harmony. Like Koelsch et al. [24], they observed an early negative deflection elicited by harmonically incongruous chords that had an onset after 200 msec and was more bilateral than right-lateralized (EAN). They further inserted infrequently mistuned chords into the sequences that violated the rule of relations between all chords in the sequence. The authors found that ERPs after mistuned chords show a bilateral fronto-central negativity around 270 msec and associate this with the MMN because tuning changes represent a violation of acoustic regularities instead of a violation of harmonic rules [27].

Further, the MMN component was found to be elicited by loudness manipulations during listening to musical sequences. Here, the amplitude of the MMN increased and the peak latency decreased with increasing deviation from the standard loudness [29]. The MMN elicited by occasional loudness increments was followed by a P3 component which is usually absent for loudness decrements of equal magnitude. This can be explained by the fact that loudness decrements tend to be less attention-catching auditory events compared to loudness increments [33].

2.2 Perception vs. Performance

While the previously presented studies investigated auditory prediction errors in non-musicians during listening to musical sequences, other studies compared auditory prediction errors in pianists during piano perception (listening) and piano performance (playing) [19, 28].

Maidhof et al. [28] conducted a study with 8 pianists who had an average of 18.5 years of formal piano training. The participants played and listened to simple piano sequences which they had to memorize before they got blindfolded during piano playing and listening. Between every 40th and 60th tone, the pitch of one tone was randomly lowered by one semitone. The sequences consisted of octaves played bimanually in different major keys and were performed on a MIDI keyboard. The authors observed an early negativity around 200 msec following manipulated tones which had a larger amplitude in the performance condition compared to the listening condition. This negative component was interpreted as a feedback error-related negativity (ERN) reflecting unexpectedly negative performance feedback. This feedback ERN is likely to be overlapped by the MMN or ERAN components because during performance, like during listening, expectancy is influenced by the preceding musical context. However, the authors suggested that the feedback ERN is distinct from the MMN and ERAN as it is associated with intention or action-based predictions [17, 28]. Consistent with the interpretation of the feedback ERN, results from source localization suggest that this component originates from neural generators in the rostral cingulate zone of the brain, which was attributed to performance monitoring [28]. This early negative component was followed by two positive peaks at 300 msec (P3a) and 400 msec (P3b) after manipulated tones. Whereas the early negativity was unaffected by task relevance, the amplitudes of the positive components in the listening condition increased if the participants had to count manipulated tones. If the manipulated tones were task-irrelevant, the P3a component was significantly larger in the performance condition compared to the listening condition.

Maidhof et al. [28] conclude that the processing of prediction errors is modulated by action, as during music performance pianists anticipate specific auditory feedback based on their intention and their act of performing. When unexpected tones are perceived without performing, this expectancy violation is solely based on the preceding musical context, which elicits a similar early negative component in the brain response but with a decreased amplitude [28].

A second study that analyzed ERPs of expectancy violations during piano performance and perception was conducted by Katahira et al. [19]. In a first experiment, they divided 15 pianists into two groups of different piano skill levels and recorded EEG data during piano performance. The first group included trained pianists with more than three years of formal piano training before the age of twelve. In contrast, the second group consisted of non-trained pianists who could read musical scores and play simple melodies on the keyboard but had not had formal piano training. They played simple right-handed melodies containing only single notes on a MIDI keyboard by sight-reading from a musical score. With a probability of 5%, the played notes were replaced by a note one semitone up. The authors hypothesized that trained musicians could predict auditory feedback based on their motor action whereas non-trained participants lack this ability. The resulting ERPs after manipulations showed a negative component around 100 msec (N1) and a second around 210 msec (N210) for the trained group that were absent in the non-trained group. The N1 component was most dominant on temporal and the N210 component on frontal and central midline scalp locations. Assuming that the motor-auditory mismatch elicits the negative components, their hypothesis was confirmed as the negative components were only observed in the trained group. Katahira et al. [19] suggest that the N210 component resembles the ERN rather than the ERAN because the ERAN reflects harmonic deviations by out-of key intervals instead of melodic deviations as in this experiment. Additionally, similar to Maidhof et al. [28], they assume that negative auditory feedback during motor action generates error-related brain responses, like the feedback ERN. Following the negative deflections, they observed a positive component in a time window from 350 msec to 450 msec for both trained and non-trained groups [19].

In the same study, a second experiment was conducted with different participants in which 7 formally trained pianists listened to similar melodies with the same manipulations as in the performance experiment. While listening to the melodies, they followed the musical score note by note without performing. Therefore, tone manipulations violated predictions not only concerning the preceding musical context but also due to an incongruity between the visually perceived note and the auditory feedback. The ERPs of manipulated tones contained a negative deflection between 150 msec and 200 msec after tone onset and are refered to as imaginary mismatch negativity (iMMN) originating from the mismatch of the visually perceived score and the corresponding sound [19]. One should note that in contrast to the study of Maidhof et al. [28], which followed a within-subject design, the study by Katahira et al. [19] recorded data of different participants in performance and perception experiments.

Both presented studies about ERPs during listening and playing of piano sequences induce expectancy violations by manipulating the pitch of single tones by one semitone. As prior studies about music perception, however, indicate that different types of acoustic deviations elicit distinct ERP responses, the goal of this thesis is to compare ERPs of auditory expectancy violations in piano performance and perception for different types of acoustic manipulations. For this, we compare ERP responses to two types of pitch and loudness manipulations, respectively.

3 METHODS

In this paper, we compared ERPs following auditory prediction errors in piano performance and perception for four different types of feedback manipulations at the time of a keystroke or perceived tone. To investigate the specificity of the signal, we compare both action conditions (performance vs. perception) to clarify the role of motor action with respect to motor-auditory mismatches during music performance and its interaction with expectancy violations in distinct acoustic features.

We designed a study in which experienced pianists listened to predefined piano sequences and played the same sequences on a manipulated MIDI keyboard. Systematically, either pitch or loudness manipulations were integrated into the piano sequences by changing the underlying MIDI messages in real time. Pitch manipulations were designed in such a way that they sounded either harmonic or dissonant within the corresponding key of the sequence. Additionally, two distinct types of loudness manipulations were designed that were either a small or a large increase in loudness of a single tone, resulting in four different types of auditory prediction errors in the experiment.

We hypothesized prediction errors in the performance condition to elicit larger ERP amplitudes compared to the same prediction errors in the perception condition [28]. Furthermore, we hypothesized that violation of harmonic prediction by either dissonant or harmonic pitch manipulations and violation of musical regularity by either small or large loudness manipulations have different effects on the elicited ERP components.

3.1 Participants

Data from 7 trained pianists were recorded for this experiment. Three participants identified themselves as female, four as male. They were all right-handed and had an average age of 34.9 years (SD = 9.2). Participants were admitted to the experiment if they had at least 5 years of formal piano training of any musical style and were able to read musical scores. They had, on average, 20.4 years of formal piano training (SD = 15.2). All participants reported no current neurological conditions or use of medication affecting the central nervous system and had normal or corrected to normal vision. Participants were compensated with 10€ per hour. A self-assessment questionnaire from the local ethics committee confirmed the study design to be ethically harmless and all participants provided written informed consent prior to their participation.

3.2 Setup

In the following, the equipment used in the experiment consisting of the keyboard, audio and EEG setup is described.

3.2.1 Keyboard and Audio. Participants played on a Nektar Impact LX25+ MIDI-keyboard (Nektar Technology, Inc, Glendale, California, USA) which produced piano sound generated by Ableton Live's (Ableton AG, Berlin, Germany) standard grand piano instrument (Grand Piano.adg). They listened to their performances and piano sequences via Audio-Technica ATH-M50 (Audio-Technica Ltd., Leeds, UK) monitor headphones with the same comfortable volume setting, see figure 2a for the full setup.

3.2.2 EEG Setup. EEG data was recorded from 64 actively amplified electrodes using Brain Products actiCAP electrode cap and BrainAmp DC amplifiers (BrainProducts GmbH, Gilching Germany). Electrodes were placed according to the extended 10-20 system with an additional electrode placed under the right eye tracking vertical eye movements. After fitting the cap, all electrodes were filled with conductive gel to ensure proper conductivity and electrode impedance was brought below 10 kOhm where possible.

EEG data were recorded with a sampling rate of 250 Hz. EEG data and a marker stream that marked events of the experiment were synchronized using labstreaminglayer[1]. Markers were sent to the stream for every MIDI-message, that is every performed or perceived tone.

3.3 Stimulus material

In the performance condition, participants had to repeatedly play piano patterns in different major and minor keys of a length of 2 bars with their right hand given by a musical score. In the perception condition, participants listened to the same collection of piano patterns (forming a musical sequence). All notes were chords of three keys pressed at the same time. The piano patterns were played at a constant tempo and contained only quarter notes in four-quarter time leading to equal time intervals between notes. The tempo was approximately 100 beats per minute (bpm), that is, each chord was performed or perceived approximately every 600 msec. All patterns consisted of three different chords in various keys and orderings, resulting in 20 different but structurally similar piano patterns, see figure 2b for an example. The three chords for each pattern were determined by the cadence of the corresponding key which is a sequence of three chords that together contain all tones of the scale and therefore determine the key of the pattern with a minimum number of chords. This allowed for systematic integration of harmonic and dissonant pitch manipulations within short piano patterns by changing a single note of a chord. Inversions of the chords were chosen in a way that minimizes the required arms movements of participants in the performance condition.

3.4 Experimental design

The experiment had a 2 x 5 within-subjects design with two action conditions (performance, perception) and five event types (no manipulation, harmonic pitch manipulation, dissonant pitch manipulation, small loudness manipulation, and large loudness manipulation).

3.4.1 Manipulations. In the performance condition, auditory feedback from keystrokes was manipulated pseudo-randomly in a range between every 10th and 20th produced note such that pianists did not hear the tone of the pressed key, but a tone with a different pitch or loudness. The type of manipulation was pseudo-randomly chosen among the four different types with the constraint that each of them occurred equally frequently in each action condition resulting in 45 trials per participant in each action condition for each of the four investigated types.

Manipulations were executed by a Python program that changed incoming MIDI messages from the MIDI keyboard before sending them to the music software Ableton Live for generating the piano sound output. In the perception condition, the Python program sent sequences of MIDI messages that were consistent with the piano patterns in the performance condition to Ableton using time intervals that correspond to the same tempo of 100bpm. The program manipulated these MIDI messages analogously to the performance condition.

[1]https://github.com/sccn/labstreaminglayer, last accessed 13/9/2022

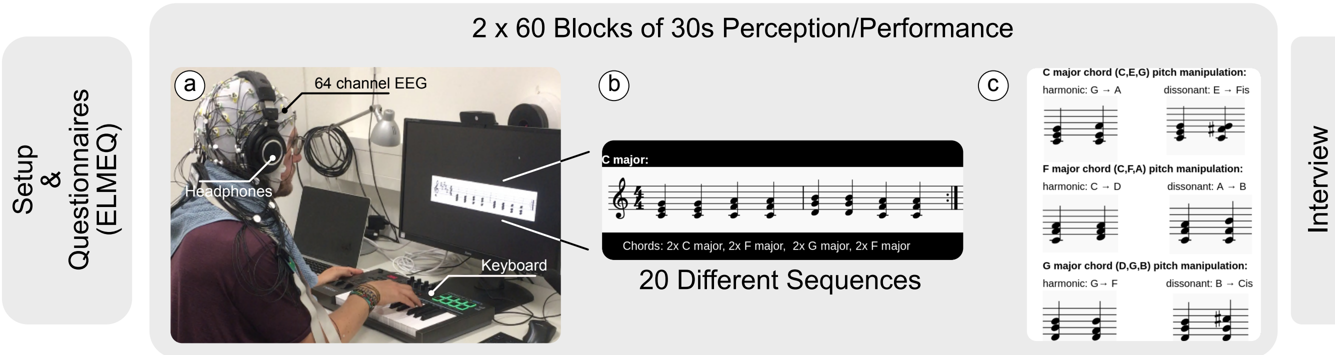

Figure 2: *Setup* a: Photograph (taken with consent) of one of the pianists that participated in this study. Participants were seated in front of a screen showing musical scores. They were equipped with an EEG system and wore stereo headphones while playing a MIDI keyboard. b: Exemplary pattern out of 20 different piano patterns of two-bar length that the pianists played and listened to. c: To realize harmonic and dissonant pitch manipulations one out of three tones of a chord was changed. This example shows a pitch manipulations in the C major key pattern. The first and second chords show unmanipulated and manipulated chords, respectively. The main experiment was preceeded by the setup and administration of the ELMEQ questionnaire. In the end, a brief exit interview was conducted.

Pitch manipulations were realized by changing note numbers whereas loudness manipulations were realized by changing the velocity values of the MIDI message. Two different types of pitch manipulations were designed that either sounded harmonic or dissonant within the key of the currently played sequence. Harmonic pitch manipulations changed the tone number of a single tone within a chord in a way that the resulting chord was part of the chords that were built on the scale of the same key. Dissonant pitch manipulations, in contrast, manipulated note numbers of single tones within a chord such that dissonant intervals between the notes of the chord arose. Figure 2c illustrates how harmonic and dissonant pitch manipulations were realized for the chords of the C major key pattern, shown in figure 2b. Whereas harmonic pitch manipulated chords sound correct in terms of harmony but are different to the originally played chord, dissonant pitch manipulations let the chords sound harmonically unexpected and incongruous.

Loudness manipulations increased the velocities of incoming MIDI messages of single tones within the chords to either a set value of 100 or 115 resulting in louder or much louder perceived tones as originally played. Non-manipulated tones had an average velocity value of 51 corresponding to a medium loudness level.

3.5 Procedure

Before starting the EEG experiment, the participants filled out questionnaires regarding socio-demographic information and health characteristics and their musical skill level, i.e. the Edinburgh Lifetime Musical Experience Questionnaire (ELMEQ) [31], see general procedure depicted in figure 2. They were informed about the occasional wrong feedback of the piano and asked not to stop after unexpected piano feedback or if they committed an error. They were also told that they will not be evaluated based on their performances.

Each participant then completed 120 pseudo-random blocks of either performing or perceiving piano sequences such that each action condition occurred 60 times. The piano pattern for each block was pseudo-randomized with the constraint that each of the 20 patterns occurred 3 times in each action condition and no pattern is followed by the same pattern in the next block. Each block had a short duration of approximately 30 seconds to allow for frequent changes of piano patterns to minimize effects of habituation. In each block of the performance condition, the pianists were shown the notes of the piano pattern and were given time to practice it until they were able to play it confidently. A standard metronome was played back for 4 seconds to indicate the tempo of 100 bpm. The pianists were instructed to repeatedly play the piano pattern in the given tempo until the next pattern appeared on the screen after 30 seconds. They were told to play the piano patterns accurately and at a constant medium loudness level. In the perception condition, participants had to listen to piano sequences for 30 seconds while fixating a white cross on the screen in front of them. In these blocks, they had no other tasks to accomplish and were told to relax. After every 20th round, participants had a 3-minutes break. The experiment took approximately 2 hours including around 30 minutes of performance, 30 minutes of perception, instructions, and breaks.

After the experiment, participants were asked whether they noticed something strange during performing which all except one participant answered with 'yes'. To the question whether they think that they have had an influence on this strange behavior, all participants answered with 'no'.

3.5.1 EEG Preprocessing. EEG data was preprocessed using the BeMoBIL-pipeline inside the MATLAB environment that includes wrappers of EEGLAB[2] toolboxes [20]. The inherent delay of the BrainVision EEG setup using LSL was corrected by subtracting 60 msec of the timestamps[3]. After removing non-experiment segments, bad channels were detected using the 'FindNoisyChannel' function, which is selecting bad channels by amplitude, the signal

[2]https://sccn.ucsd.edu/eeglab/index.php, last accessed 13/9/2022
[3]https://wiki.bpn.tu-berlin.de/wiki/doku.php?id=lab:lab_software:lsl:lsl-test

to noise ratio and correlation with other channels [3]. Rejected channels were then interpolated while ignoring the EOG channel, and finally re-referenced to the average of all channels including the original reference channel FCz. After applying a high-pass filter at 1.5 Hz, time-domain cleaning and outlier removal was performed using AMICA auto rejection. Eye artifacts were removed using the ICLabel toolbox applied to the results from an AMICA [32]. For this, the popularity classifier was used, meaning that all components having the highest probability for the eye class were projected out of the sensor data.

3.5.2 Extracting ERP data. To calculate ERPs, EEG data was filtered with a 0.1 Hz high-pass and 15 Hz low-pass filter. The data was epoched for tone onsets generated by keystrokes in the performance condition or auditory perceived tones in the perception condition. As the piano sequences were played and listened to with a tempo of approximately 100 bpm corresponding to a 600 msec time interval between tones, the epoching window was defined from 100 msec before to 600 msec after tone onset. To ensure robust analysis results, 15 % of the noisiest epochs were rejected using the EEGLAB *auto_rej* function.

A chord detection algorithm summarized each three-note events that formed a single chord to one corresponding event. Furthermore, all non-regular chord events that contained less or more than three simultaneously pressed notes as well as chords having an out-of-range inter-chord interval of less than 520 msec or more than 680 msec were excluded from the data. For baseline correction, the average of all EEG samples from -100 msec to 0 msec was calculated and subtracted from all EEG samples for each epoch.

3.5.3 ERP analysis. First, we inspected ERPs at electrodes AF4 and the midline electrodes AFz, Fz, FCz, Cz and CPz due to their frequently exhibiting effects in related works. Ultimately, we chose to report results for electrode FCz due to it being reported most frequently in the literature on prediction error processing, see related work section. Furthermore, here we found the strongest signal deflections.

In a first step, grand average ERPs including all events of all participants were plotted for regular and manipulated tones in the performance and the perception condition, irrespective of the type of manipulation.

For statistical assessment, we conducted a mass-univariate ERP analyses [16]: for each time point of the epoch (= 175 timepoints for the -100ms to 600ms interval sampled at 250Hz), linear mixed-effects models that take into account dependence of data within subjects were fit using the Python toolbox 'statsmodels' [36]. The full model was specified with the categorical variables *action* (perception, performance), *manipulation type* (no manipulation, harmonic pitch manipulation, dissonant pitch manipulation, large loudness manipulation, small loudness manipulation), and their interaction (linear mixed model: $FCz \sim action * manipulation, groups = participant$).

For each main effect, likelihood-ratio test statistics (χ^2) and p-values were calculated. Since we tested each time point (175 tests in total) we applied p-value correction using the false-discovery rate (FDR [2]) at alpha = 0.01. χ^2-values and corrected p-values of each main effect were stored for each time point and time points with corrected p-values smaller than 0.01 were highlighted for each effect in the ERP plots.

As a second step, to analyze the effects of the four different manipulation types, we investigated the beta estimates of the previously computed full model $FCz \sim action * manipulation, groups = participant$, see above. Here, the not-manipulated condition served as the intercept condition. For each time point beta estimates as well as FDR-corrected p-values were stored for each of the four manipulation types. Finally, difference waves for each manipulation type obtained by subtracting ERPs of normal tones from ERPs of manipulated tones were aggregated for plotting. For significance masking, time points were marked that that exhibited corrected p-values smaller than 0.01 obtained by the linear mixed model.

It should be noted that in the performance condition time intervals between chords can vary if participants fall out of the instructed tempo of 600 msec between chords while chords in the perception condition are always exactly 600 msec apart. Therefore, the last 100 msec of the ERP epoch were not interpreted.

We encourage readers to reproduce and extend our results and analyses methods. Therefore our experimental setup, preprocessed datasets and analyses scripts are available at: https://github.com/lukasgehrke/piano-EEG.

4 RESULTS

ERPs of normal tones without manipulation in both performance and perception conditions exhibited two positive deflections with peak latencies of approximately 100 and 200 msec after tone onset.

4.1 ERPs of Auditory Prediction Errors

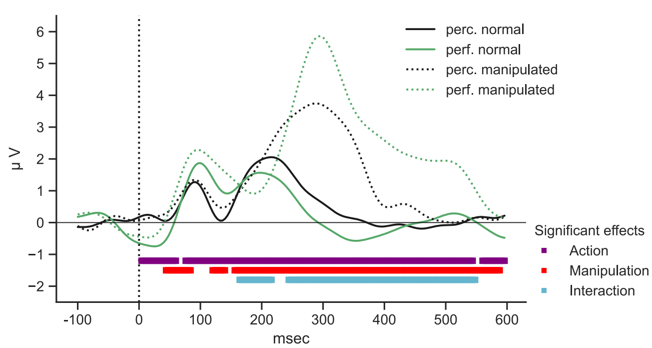

Figure 3: Grand average ERPs at electrode FCz for normal (solid lines) and manipulated (dotted lines) tones in the perception (perc., green) and performance (perf., black) condition. Time intervals with significant effects of action, manipulation and their interaction are indicated by colored bars on the bottom.

A main effect of action was observed for nearly all time points. The maximum effect was found at 12ms after tone onset ($\chi(5) = 331.24$, p < .001)[4]. While the time courses for action showed broad

[4]Effects in the baseline period were not tested, nor were they visualized. While this time point is too early for an ERP response, we chose to test every time point after the tone event and reported the findings accordingly

similarity in amplitude, a temporal shift was visible. In the performance condition, the time course appeared to be shifted slightly towards a later time.

A first effect of manipulation was observed in a window around 50-80ms after the tone event. Furthermore, manipulation impacted the ERP at almost all time points from around 120ms onward (maximum effect at 290ms, $\chi(8) = 1119.4$, p < .001). In the perception condition, the effect was reflected by a positive deflection with a peak latency of around 300 msec. In the performance condition, the ERP first decreased in amplitude. The decrease was followed by a positive deflection with a peak latency of again 300 msec. Compared to the perception condition, this positive deflection had a larger amplitude with a prolonged temporal extent.

Manipulations had a different effect on the ERPs of both action conditions starting at around 160ms onward with a maximum effect at 280ms ($\chi(4) = 113$, p < .001).

4.2 Difference Waves: Comparing Different Types of Manipulations

All difference waves showed a small negative component with peaks in the time window from 180 msec to 240 msec after tone onset followed by a larger positive component with peaks in the time window from 250 msec to 340 msec. The peak latencies varied depending on the manipulation type and action condition. For pitch manipulations a second smaller positive peak was observed in the time window from around 440 msec to 480 msec, mostly pronounced in the performance condition.

In the perception condition, see Figure 4 a, ERPs of dissonant pitch manipulations showed a negative deflection that was significant from around 200 msec to 220 msec after tone onset. In two time windows from 250 msec to 375 msec and from 425 msec to 485 msec, ERPs of dissonant pitch manipulations had significant positive components with peaks at around 310 msec and 450 msec, respectively (maximum beta at 311ms, $beta = 3.6, p < .001$). For harmonic pitch manipulations in contrast, the corresponding negative component, having had a smaller amplitude and larger peak latency of around 240 msec, was not found to be significant. As for dissonant pitch manipulations, it was followed by two positive deflections. The first positive deflection was found to be significant and revealed a larger latency and similar amplitude compared to the same component in dissonant pitch manipulations (maximum beta at 340ms, $beta = 2.9, p < .001$). The shorter peak latencies for dissonant pitch manipulations indicate a faster brain response compared to for harmonic pitch manipulations.

For large loudness manipulations, the negative component with peak latency at around 180 msec was not found to be significant. It was preceded by a significant positive component from around 120 msec to 140 msec. A large significant positive deflection could be observed from around 200 msec to 400 msec with peak latency of around 250 msec (maximum beta for large loudness manipulations at 260ms, $beta = 1.6, p < .001$). For small loudness manipulations, the negative deflection from around 180 msec to 200 msec, having had a similar amplitude as the same deflection after large loudness manipulations, was not found to be significant. It was followed by a significant positive component from around 260 msec to 340 msec that had a shorter significant time window and smaller amplitude compared to the corresponding positive component for large loudness manipulations (maximum beta at 308ms, $beta = 3.6, p < .001$), showing a stronger brain response for large compared to small loudness manipulations.

In the performance condition as illustrated in Figure 4 b, pitch manipulations showed two positive peaks at around 310 msec and 450 msec for dissonant pitch manipulations and around 320 msec and 470 msec for harmonic pitch manipulations with the second peaks having been smaller in amplitude than the first peaks. The peaks had shorter latencies and larger amplitudes for dissonant compared to harmonic pitch stimuli indicating a slightly stronger brain response. Significant effects were obtained starting from 325 msec and around 375 msec after tone onset for dissonant ($beta = 3.5, p < .001$ at 384ms) and harmonic pitch manipulations ($beta = 2.38, p = .002$ at 508ms), respectively. They were preceded by negative deflections around 220 msec for dissonant pitch manipulations and 240 msec for harmonic pitch manipulations that were not significant.

A significant negative effect was observed for large loudness manipulations in a time window from around 160 msec to 220 msec with a negative peak around 190 msec. Two time windows from 240 msec to 340 msec and from 380 msec to 400 msec with peak latencies of 280 msec and 390 msec showed significant positive effects ($beta = 1.3, p = .01$ at 284ms). Small loudness manipulations, in contrast, showed one time window with a significant positive effect from 240 msec to 360 msec with its peak at 290 msec that had a smaller amplitude compared to the corresponding component for large loudness manipulations ($beta = 1.6, p = .03$ at 292). The preceding negative deflection with a peak at around 190 msec was smaller in amplitude compared to the same component for large loudness manipulations and was not found to be significant. Like in the perception condition this shows a stronger brain response to large compared to small loudness manipulations.

5 DISCUSSION

The goal of our study was to find out whether ERPs from pianists are sensitive to fine-grained acoustic deviations in pitch and loudness while comparing two action conditions, piano perception and piano performance. In our study with 7 pianists, we found that manipulations during performance elicited larger amplitudes compared to during perception hinting at the fact that the embodied piano performance impacts the sensitivity of the sensory apparatus to auditory prediction errors. We found that loudness manipulations, violating musical regularity, elicited deflections with smaller peak latencies compared to pitch manipulations that violate harmonic expectancy.

5.1 Detailing ERP Components of Auditory Prediction Errors

Based on related work of Maidhof et al. [28], it was hypothesized that prediction errors in the performance condition elicit larger brain responses compared to the same expectancy violations in the perception condition [28]. This was confirmed by the results of our study showing larger peak amplitudes in ERPs of manipulated tones in the performance condition compared to the perception condition. As pianists control the pitch and loudness of tones during their performance by pressing specific keys with a specific force,

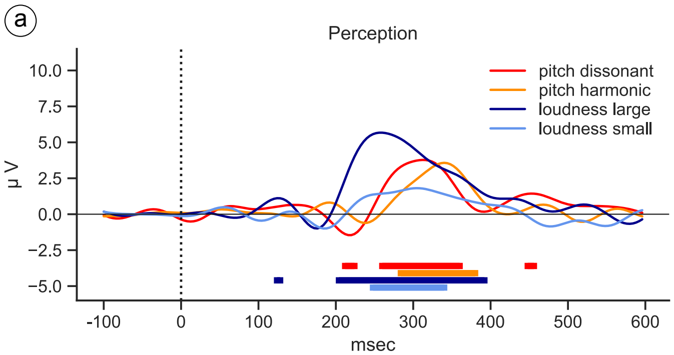

Figure 4: Difference waves at electrode FCz obtained by subtracting ERPs of normal tones from ERPs of manipulated tones for Perception (a) and Performance (b). Light orange and dark orange lines correspond to harmonic and dissonant pitch manipulations whereas light blue and dark blue colors correspond to small and large loudness manipulations. Time intervals with significant effects of each manipulation type are indicated by color-coded bars on the bottom.

it can be assumed that higher accuracy is placed on auditory predictions during piano performance compared to piano perception leading to stronger expectancy violations caused by manipulations. With regard to the underlying brain mechanisms, this refers to the motor-auditory feedback loop that allows for self-monitoring and processing of fulfilled and violated predictions during music performance by relating motor action to auditory feedback and vice versa [42].

Differences between the ERPs of manipulated tones in perception and performance conditions were more pronounced for loudness manipulations compared to pitch manipulations. Relatively to the perception condition, this indicates that pianists during performance create stronger predictions on loudness compared to pitch due to the strongly internalized relationship between the force of a performed keystroke and the loudness of the resulting tone.

Assuming that expectancy violations of distinct acoustic features are processed in a different way, we hypothesized that violation of harmonic expectancy by dissonant and harmonic pitch manipulations and violation of musical regularity by small and large loudness manipulations have different effects on the ERPs. The results of our study show smaller latencies of negative and positive peaks at ERPs for loudness manipulations compared to ERPs for pitch manipulations in both conditions. This indicates that loudness manipulations elicited faster brain responses compared to pitch manipulations. Further, this finding hints at different neural processes being at play mapping predicted to perceived tones with respect to pitch and loudness. This highlights the importance to distinguish between different acoustic features when investigating auditory expectancy violations.

When comparing dissonant pitch manipulations to harmonic pitch manipulations and large loudness increases to small loudness increases, the peak amplitudes were larger and the peak latencies were shorter. These differences were more pronounced for small and large loudness manipulations compared to harmonic and dissonant pitch manipulations. The overall largest negative and positive deflections were caused by large loudness manipulations in the performance condition showing that unexpected loud tones during playing the piano elicit particularly strong brain responses.

It is likely that our findings behave similarly for other kinds of instruments that allow for loudness and pitch control with equal precision by a similar way of moving the fingers. These results can not be applied directly to other instruments that have different ways to modulate loudness and pitch. For example, some instruments like violins allow for a more precise way to control the pitch or others have a different tonal structure with respect to pitch like atonal instruments in eastern music.

Further, it is interesting to note that strong signal deflections, presumably arising during multisensory integration, were previously also observed in manipulations of other sensory modalities, for example during visuo-haptic integration [12, 14]. This hints at an underlying process of prediction errors being propagated through the brain hierarchy during predictive processing [7].

5.2 Limitations

The motor cortex of pianists can be activated by solely listening to piano pieces without the execution of movements [18]. Therefore, while the intention to produce a tone and the corresponding action only happens in the performance condition, activation of the motor cortex in pianists cannot be completely excluded in the perception condition.

Furthermore, in our performance condition, participants had to read the notes from musical scores. This was due to the implementation of dissonant and harmonic pitch manipulations that required the use of different predefined piano patterns in various keys that were hard to memorize. As participants were looking at the scores while playing, effects caused by visual processing cannot be ruled out. For example, some studies observed visual-auditory mismatch negativities in experiments where pianists looked at musical scores while listening to manipulated sounds from the scores [40] Katahira et al. [19]. As in our study, however, scores were used for performing not for listening, we attribute the observed mismatch negativities to motor-auditory mismatches instead of visual-auditory mismatches. Nevertheless, to exclude potential overlapping effects of visual processing, future studies are needed that generate distinct types of pitch manipulations during piano performance without the need to use scores.

The piano patterns in this experiment were kept simplistic to be able to generate comparable harmonic and dissonant pitch manipulations in different tonalities. To create a more realistic scenario, future studies might use elaborated algorithms to identify the tonality in real-time while pianists improvise or play their own songs on the piano. Such a flexible approach would allow to evaluate whether the musical genre or modality of playing, either from score or improvising, influences the brain response to auditory expectancy violations.

While the pianists in our study come from a variety of musical backgrounds, it would be valuable in further studies to investigate brain responses of pianists of specific backgrounds or musical cultures, like for example jazz pianists compared to classical pianists.

5.3 Contributions

In this paper, we contributed towards a new approach to obtain an implicit metric of sensory-motor accuracy. By conducting an EEG study, we demonstrated the general feasibility to obtain discriminatory diagnostics of sensory-motor accuracy by probing event-related brain responses of pianists using irregular system outputs. We observed distinct temporal EEG features to reflect different acoustic properties as well as their coupling to whether participants were playing the piano or listening to a piano recording. In the future, such an approach might thus complement objective performance metrics.

5.3.1 Towards Intelligent Music Interfaces. While we conducted our study in the lab, our findings were obtained from a realistic application scenario and represent a first step towards the application of (neuro-)intelligent music interfaces, see Knees et al. [21] for a detailed overview on the topic. To adapt musical content, interaction and feedback presentation intelligent music interfaces employ natural language, gestures, or physiological inputs, rather than traditional interface methods such as piano keys, buttons and touchscreens [6]. We foresee several specific application scenarios where our work contributes further.

First, our results showed that we could discriminate between expectancy violations based on loudness and pitch manipulations. By conducting further studies with test subjects of different skill levels and musical backgrounds, we foresee great opportunities in identifying weakness and strengths of musicians derived from their sensory-motor accuracy with respect to different acoustic properties. This would enable a system to adaptively display educational content such as lessons, scores, and exercises. Crucially, such educational content may then be delivered via wearable actuators, such as electrical muscle stimulation in order to 'teach' fine-tuned motor output [13, 15].

Second, besides applications for performance and learning, intelligent music interfaces may also find applications in affective computing for emotion regulation [8]. While recent closed-loop systems for artistic (musical) expression primarily focused on the use of EEG frequency features such as alpha oscillations [11] or a combination of different rhythms [9, 35], future work may entertain the usage of auditory ERP components, considering that both MMN and ERAN have been shown to hold discriminative power over affective state changes during exposure and performance [5, 10].

5.4 Conclusion

We found that auditory feedback manipulations during piano performance elicited generally larger brain responses compared to when the pianists were only listening to them. We conclude that the intention and action of producing a specific sound during playing the piano form a stronger prediction on auditory feedback compared to the predictions based on the musical context during listening. Further, we observed that loudness manipulations that broke musical regularity-based expectations led to positive and negative ERP components with shorter latencies than pitch manipulations that broke harmonic expectations. We conclude that expectancy violations of distinct acoustic features are processed by the brain in a different way. Therefore, future studies on auditory expectancy violations may take into account different sound components such as pitch, loudness, timbre, and timing to contribute to a better understanding of how the brain forms expectancy in music.

ACKNOWLEDGMENTS

Lukas Gehrke was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Project ID GR 2627/13-1. Francesco Chiossi was supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Project ID 251654672 TRR 161.

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