

# Sensory feedback in music performer–instrument interactions

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## Abstract

Musical performance involves the production of highly accurate sequences of movements in space and time. During a performance, real-time auditory, visual, somatosensory (tactile and kinematic), and movement-related information of the outcome of an action provided within the different sensory systems is integrated into a coherent percept and fed back to the motor system. These sensory feedback mechanisms are, therefore, crucial to maintaining the fluency of production. However, how and to what extent do these feedback mechanisms influence music performance and learning? A growing area of research has investigated the role of different types of sensory feedback on the musicians' performance. The aim of this integrative review is to overview the recent literature on the role of sensory feedback on music performance, focusing particularly on the individual interaction between musician and instrument. In the first section, we review recent findings regarding the role of auditory, visual, and somatosensory (tactile and kinesthetic) feedback on music performance considering each sensory modality separately. To finalize, we briefly discuss the implications of these findings to support learning and pedagogical practice.

## Keywords

*sensory feedback, auditory feedback, visual feedback, somatosensory feedback, music performance*

Playing a musical instrument is a complex and multifactorial behavior that requires a number of cognitive skills, including motor planning, serial actions, sequencing, and sensorimotor integration (Palmer, 2013). Performing even a simple musical piece requires precise control of timing of hierarchically organized actions and precise control over sound production (Zatorre,

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Chen, & Penhune, 2007). Considering that each action in a music performance produces correlated perceptual outcomes (auditory, visual, somatosensory) that will influence each subsequent movement, it is of fundamental importance to understand the role of sensory feedback mechanisms in maintaining the fluency of production in music performance.

A common approach to studying how and to what extent sensory feedback influences movement execution and planning is by experimentally manipulating the perceptual feedback of an action (Kulpa & Pfordresher, 2013; Pfordresher & Dalla Bella, 2011; Pfordresher & Palmer, 2006). A growing area of research has investigated the role of different types of sensory feedback on the performance of musicians; however, this literature is scattered across time. This article aims to review the recent literature on the role of sensory feedback on music performance, focusing particularly on behavioral research regarding the individual interaction between musician and instrument. In the first section, we review recent findings regarding the role of auditory, visual, and somatosensory (tactile and kinesthetic) feedback on music performance, considering each sensory modality separately. To finalize, we briefly discuss the implications of these findings to support learning in a music education context.

## **Sensory feedback mechanisms involved in music performance**

Musical performance involves the production of highly accurate sequences of movements in space and time. When playing the piano, for instance, temporal and spatial precision of finger and hand movements on the keyboard are crucial to achieving an accurate and satisfying performance (Dalla Bella & Palmer, 2011; Furuya & Soechting, 2010). During a performance, real-time auditory, visual, somatosensory (tactile and kinematic), and movement-related information of the outcome of an action provided within different sensory systems is integrated into a coherent percept and fed back to the motor system to rapidly adjust subsequent motor actions (Kawato, 1999; Seidler, Noll, & Thiers, 2004). These feedback mechanisms are, therefore, crucial to maintaining the fluency of production. However, how and to what extent do these feedback mechanisms influence musical learning and performance? In this section, we provide an overview of recent research findings on the different roles of sensory feedback on music performance.

### ***Auditory feedback***

Performance-based music-making relies heavily on close auditory–motor interactions as most musical instruments involve the execution of a sequence of movements to produce an intended sequence of sounds. The perceived auditory consequences of one's actions are referred to as auditory feedback.

It is well established that auditory feedback facilitates learning of a novel task (Brown & Palmer, 2013; Engel et al., 2012; Lappe, Lappe, & Keller, 2018; Pau, Jahn, Sakreida, Domin, & Lotze, 2013; Pfordresher, 2012). This effect has been demonstrated in studies where nonmusicians learned to play musical sequences on the piano under different auditory feedback conditions (e.g., normal, fixed-pitch, and random auditory feedback) (Lappe et al., 2018; Pfordresher & Chow, 2019; Pfordresher, Keller, Koch, Palmer, & Yildirim, 2011; Stewart, Verdonschot, Nasralla, & Lanipekun, 2013). For instance, Lappe et al. (2018) showed that musical novices produced more sequencing errors (i.e., higher percentage of incorrect keystrokes) on a newly learned musical sequence when auditory feedback was random and unpredictable than in the condition where the auditory consequences of the finger movement were predictable and could be deducted from conventional piano key-to-tone mapping. These findings suggest that

auditory feedback has a relevant role in movement sequencing learning and corroborate the notion that auditory feedback is important for auditory–motor consolidation and integration (Drost, Rieger, Brass, Gunter, & Prinz, 2005; Lahav, Saltzman, & Schlaug, 2007; Pfordresher et al., 2011; Stewart et al., 2013). Pfordresher and Chow (2019) examined the strength of coupling between actions and their auditory effects in a study where professional pianists and non-pianists learned to play short melodies by ear under different auditory feedback conditions: normal pitch mapping (left keys/low notes and right keys/high notes) and inverted/reversed pitch mapping. It was demonstrated that pianists who learned melodies with an inverted pitch mapping produced more errors than pianists who learned the melodies with normal auditory feedback, whereas the error rate for non-pianists did not differ between conditions. This suggests that musicians have strongly consolidated associations between actions and their expected sensory (auditory) outcomes, and that the strength of this action–perception coupling in musicians may constrain sensorimotor learning in face of new spatial configurations for pitch representation. Evidence indeed suggests that action–perception associations emerge rapidly with practice. In Bangert and Altenmüller (2003), musical novices learned short piano melodies either with a conventional key-to-pitch mapping or with random pitch-to-key maps. Electroencephalography data were recorded immediately before and after the first training session and again after 5 weeks of training. The results demonstrated that while a distinct right anterior activation was observed in the group that learned the melodies with normal auditory feedback, this activity was absent when pitches were randomly assigned to each piano key preventing associations. These findings indicate that auditory–sensorimotor coactivation associated with the establishment of a key-to-pitch map emerges after a few minutes of practice and is firmly established after a few weeks of training (see also Baumann et al., 2007; Chen, Rae, & Watkins, 2012).

Auditory–motor associations acquired through learning may also facilitate auditory memory (Brown & Palmer, 2012; Brown & Penhune, 2018; Engel et al., 2012; Finney & Palmer, 2003; Palmer, 2005; Pau et al., 2013). Brown and Palmer (2012) showed that pianists' recognition of newly learned musical sequences was generally better when auditory feedback was provided during practice (auditory-only and auditory–motor conditions) in relation to learning the melodies by performing with no sound (see also Brown & Penhune, 2018). In addition, the study indicated that auditory memory was better for melodies that were performed with normal feedback than following auditory-only learning. Schiavio and Timmers (2016) expanded these findings by examining the role of motor and audiovisual learning in auditory memory in participants with different levels of piano experience. Participants (nonmusicians, pianists, and other musicians) learned tonally ambiguous piano melodies by playing the melodies with auditory feedback, by silent playing, by watching a video of someone playing the melodies, or by only listening to the melodies. The results indicated that the proportion of correctly recalled melodies was higher in the learning conditions where there was active motor engagement (playing with and without feedback) than in the auditory-only condition for all participants, instigating further research on the role of active sensorimotor experience in learning and auditory memory.

There is also substantial evidence that auditory feedback is important to regulate the timing of movement sequencing in sensorimotor synchronization (for extensive discussion, see Aschersleben & Prinz, 1995; Pfordresher, 2003; Pfordresher & Dalla Bella, 2011; Pfordresher & Kulpa, 2011; Repp, 2005; Repp & Su, 2013). Findings consistently show that maintaining the metronome tempo in a synchronization-continuation finger-tapping task is significantly more variable when no auditory feedback is provided than when self-feedback is available (Konvalinka, Vuust, Roepstorff, & Frith, 2010; Mates, Radil, & Pöppel, 1992; Nowicki, Prinz,

Grosjean, Repp, & Keller, 2013; Schultz & Palmer, 2019). This suggests that internal mechanisms that support movement adaptation and anticipation use real-time sensory feedback—such as auditory input—to control and make behavioral adjustments via timekeeping mechanisms to allow temporal coordination and action synchrony with regular external stimuli and between co-performers (Van der Steen & Keller, 2013). Indeed, joint actions require the ability to monitor the timing of one's own and others' actions to modify subsequent motor plans when asynchronies occur, which is done particularly successfully when auditory information from all parts is available (for review, see Keller, Novembre, & Hove, 2014; Sebanz & Knoblich, 2009). Goebel and Palmer (2009) investigated how auditory feedback influences performance synchronization in a piano duet. Pianists performed a set of melodies while receiving only self-feedback, full auditory feedback from both parts, or while one musician received full feedback and the other received only self-feedback. It was demonstrated that temporal asynchronies increased as auditory feedback decreased. More specifically, pianists were more synchronized and showed greater adaptation in conditions in which performers received auditory feedback from the co-performer. These findings have been corroborated and expanded by studies investigating ensemble synchrony in duets (Bishop & Goebel, 2015; Loehr, Kourtis, & Brazil, 2015; Zamm, Pfordresher, & Palmer, 2014) and string quartet performance (Timmers, Endo, Bradbury, & Wing, 2014; Wing, Endo, Bradbury, & Vorberg, 2014).

While auditory information is particularly relevant for ensemble cohesion in music performance, solo piano performance appears to be relatively unimpaired by the removal of auditory feedback (Bishop, Bailes, & Dean, 2013; Finney & Palmer, 2003; Highben & Palmer, 2004; Repp, 1999). Altering auditory feedback by providing information that corresponds to a transposed version of a melodic sequence or presenting random and unpredictable pitch feedback has negligible effects on the performance of well-rehearsed and memorized musical sequences (Finney, 1997; Pfordresher, 2005, 2008). This effect is probably due to anticipatory imagery that compensates for the missing or irrelevant feedback information. Online musical imagery is the ability to experience the outcome of an action in advance of their performance or perception, and anticipatory imagery seems to enable action planning and expressive music performance whether auditory feedback is available or not (Bishop et al., 2013; Keller, Dalla Bella, & Koch, 2010). However, existing evidence suggests that performance may be affected both by the timing of feedback onset in relation to the action and by the content of the auditory feedback (Pfordresher, 2012).

A large body of research has investigated the effect of auditory feedback disruption on the production of sequential movements (Furuya & Soechting, 2010; Hove, Balasubramaniam, & Keller, 2014; Lappe, Steinsträter, & Pantev, 2013; Pfordresher & Benitez, 2007; Pfordresher & Dalla Bella, 2011; Pfordresher & Kulpa, 2011; Pfordresher & Palmer, 2006; Repp, 2001, 2008; Repp & Keller, 2008; Van der Steen, Molendijk, Altenmüller, & Furuya, 2014). It has been systematically demonstrated that auditory feedback disruptions caused by delayed auditory feedback (i.e., where a constant lag is inserted between action and auditory feedback onset) significantly affect the fluency of production primarily by slowing production rate and increasing timing variability (Pfordresher & Benitez, 2007; Pfordresher & Dalla Bella, 2011; Pfordresher et al., 2011; Pfordresher & Palmer, 2002; Repp, 2000, 2001; Repp & Su, 2013). On the contrary, the findings relating to the effect of disruptions of the content of auditory feedback (e.g., pitch, loudness) have been less consistent due partly to the implementation of distinct research paradigms. For instance, earlier results suggested that altering pitch feedback would cause little interference on performance (Finney, 1997). However, this conclusion has been challenged in a series of studies by Pfordresher and colleagues based on the serial shift paradigm (Pfordresher, 2003, 2008; Pfordresher & Benitez, 2007; Pfordresher & Kulpa, 2011; Pfordresher, Mantell,

Brown, Zivadinov, & Cox, 2014; Pfordresher & Palmer, 2006). In this paradigm, pianists perform melodies from memory while the feedback triggered by each keystroke matches a tone intended for a different sequence position (Pfordresher & Palmer, 2006). Overall, these studies show that alterations of feedback content through serial shift significantly disrupt performance by increasing error rates (i.e., striking the wrong key) but have little effect on timing variability. However, recent studies have adapted the serial shift paradigm to include only occasional auditory feedback shifts (Mathias, Gehring, & Palmer, 2017, 2019) and revealed that transient pitch perturbations can indeed disrupt timing variability, causing pianists to slow down immediately following an unexpected pitch feedback (Mathias et al., 2017, 2019; see also Furuya & Soechting, 2010). These recently emerging results suggest that performers actively monitor the timing and the content of the perceptual outcomes of their actions and that disruptions of the auditory feedback content may also impact action planning of subsequent movements, opening new lines of enquiry.

Sensorimotor discrepancies between action and its auditory outcome may also be important to determine agency, which refers to being the agent of an action or feeling in control of one's actions and their effects (reviewed in Sevdalis & Keller, 2014). In Couchman, Beasley, and Pfordresher (2012), participants performed short melodies from memory on an electronic keyboard while experiencing altered auditory feedback in relation to its content (i.e., pitch) or synchrony. Results indicated that feedback alterations significantly decreased the experience of agency, suggesting that sensorimotor discrepancies can be used to determine authorship (see also Repp & Knoblich, 2004; Van Vugt, Jabusch, & Altenmüller, 2013).

The neural mechanisms underlying disruptive effects of altered auditory feedback on music performance remain largely unexplored. Evidence from electroencephalography research suggests that unexpected changes in auditory feedback tones generated during music performance elicit a negative event-related potential (ERP) component peaking around 100–200 ms following auditory onsets (Katahira, Abla, Masuda, & Okanoya, 2008; Loehr, Kourtis, Vesper, Sebanz, & Knoblich, 2013; Maidhof, Vavatzanidis, Prinz, Rieger, & Koelsch, 2010; Mathias et al., 2017; Ruiz, Jabusch, & Altenmüller, 2009; Ruiz, Strübing, Jabusch, & Altenmüller, 2011). It has been shown, for instance, that the amplitude of ERPs elicited after an unexpected feedback is larger during music performance than during merely listening to the sequence (Maidhof, 2013), suggesting that motor training of a specific melody enhances sensory predictions. Interestingly, studies have shown that auditory feedback may not be a prerequisite for error monitoring since brain responses can be observed even before the execution of an error (Maidhof, 2013; Ruiz et al., 2009; Shadmehr, Smith, & Krakauer, 2010). Neuroimaging research further demonstrated that alterations of pitch feedback during piano performance modulate the activity within motor regions of the brain (e.g., cerebellum and the supplementary motor area) as well as the anterior cingulate cortex (a brain region implicated in action monitoring) (Pfordresher et al., 2014). These findings collectively indicate that musical training leads to a strong auditory–motor coupling that can be observed at brain level (for review, see Novembre & Keller, 2014).

### *Visual feedback*

Considerably fewer studies have investigated the effect of self-generated visual feedback on music performance. To test the role of visual information on learning and consolidation of key-to-tone mapping, Eldridge, Saltzman, and Lahav (2010) trained nonmusicians to play a piano sequence by ear with one group of participants receiving full audiovisual feedback during training while visual feedback was deprived for the second group (i.e., visual feedback of the



hands was not available). The authors observed that participants who did not receive visual feedback during learning showed poorer ability to recognize and match the pitches to the corresponding piano keys than those who received audiovisual feedback, suggesting that visual feedback facilitated key-to-tone retention and consolidation for music beginners. Engel and colleagues (2012) also trained nonmusicians to play short musical sequences on a piano keyboard with different sensory information. One group of participants first listened to the melodies and then reproduced them on the keyboard while receiving only auditory and motor information (visual feedback of their fingers was occluded), whereas the second group observed a silent demonstration and then reproduced the melodies on a muted keyboard, thus not receiving any auditory information. This study found that participants in the visuomotor training condition learned the melodies faster than those in the audio-motor training condition. However, when asked to later recognize the learned melodies, participants in the audio-motor training were more accurate at identifying the finger movements corresponding to the melodies they learned than those in the visuomotor conditions were at recognizing the sound of the learned sequences. The authors concluded that cross-modal transfer is stronger when there is audio-motor integration during music learning (see also Hasegawa et al., 2004).

While these findings suggest that visual feedback deprivation affects learning and consolidation for music beginners, evidence suggests that visual information may be less relevant for expressive music performance for highly trained musicians. In Wöllner and Williamon (2007), experienced pianists performed from memory while auditory, visual, and kinesthetic feedback was systematically removed. The results indicated that the removal of visual feedback (i.e., musicians playing with their eyes closed) did not significantly affect the stability of the timing during the performance. The authors concluded that, as seen with auditory feedback removal, the lack of significant disruptions caused by the deprivation of visual feedback is probably associated with auditory imagery, which enables skilled performers to plan an action and anticipate its outcome even before a movement is executed or perceived (Bishop et al., 2013; Keller et al., 2010).

Kulpa and Pfordresher (2013) evaluated the effect of altered visual feedback on the production of a musical sequence. Participants learned to play an isochronous melody on a keyboard and then attempted to perform this sequence while auditory and visual feedback was manipulated (normal, absent, or delayed). For that, visual feedback during the performance was represented as a motion capture animation of the performer's hand. The study results indicated that delayed visual feedback significantly affected production rate and timing variability, suggesting that conflicting information across feedback channels and sensorimotor interference caused by the delayed visual information disrupted music performance. However, more research is warranted to further understand the impact of visual feedback disruptions on the fluency and timing of action sequences.

Visual feedback also seems to be important for sight-reading (Wristen, 2005). In Banton (1995), pianists performed a sight-reading task in conditions that included normal feedback, no auditory feedback, and no visual feedback of the hands. The results indicated that while the absence of auditory feedback did not significantly affect error rates, the removal of visual feedback of the hands caused a significant increase in errors. Importantly, the degree to which performance was affected by the absence of visual feedback was associated with the pianist's familiarity with the positioning of the hands and fingers on the keyboard. Therefore, visual feedback seems to play a role in skilled sight-reading execution as it relates to the tactile command of keyboard geography, but it is unclear whether it would also be pertinent for other instruments.

A growing body of literature has also shown that visual cues are important to guide interpersonal synchronization between musicians during ensemble performances (Bishop & Goebel, 2015, 2018; D'Amario, Daffern, & Bailes, 2018; Goebel & Palmer, 2009; Palmer, Spidle, Koopmans, & Schubert, 2019). Studies reported, for instance, that precision and consistency of synchronization between performers are affected when visual cues of the partner are removed (D'Amario et al., 2018; Kawase, 2014). It has also been shown that visual contact is particularly relevant for temporal synchronization in duo performances when auditory feedback is limited or when musical timing is irregular (Bishop & Goebel, 2015; Goebel & Palmer, 2009). These findings thus suggest that feedback from one's self and feedback from a partner are both relevant for the control of timing during music performance.

### *Somatosensory feedback*

The contribution of somatosensory information for movement control in music performance has been a topic of investigation in a large body of research (Palmer, 2013). Tactile feedback, referring to the experience of touch, and kinesthetic feedback (i.e., awareness of body posture and limb position through proprioception) are the primary focus of the studies reviewed in this section.

The role of tactile feedback in the timing of sequential movements is well-known (Aschersleben & Prinz, 1995; Gordon & Soechting, 1995). Aschersleben, Gehrke, and Prinz (2001) found that local anesthesia to the participant's fingertips led to a significant increase in negative asynchrony as tapping movements preceded the pacing signals due to the suppression of tactile feedback. The study also reported that other behavioral tasks that did not involve tactile feedback (e.g., finger wiggling) were not affected by the local finger anesthesia, thus supporting the notion that tactile information plays an important role in the control of timing in synchronization tapping. These results were later corroborated in a study involving cases of patients with peripheral somatosensory loss, which causes complete loss of cutaneous touch and kinesthetic sense. In Stenneken, Prinz, Cole, Paillard, and Aschersleben (2006), healthy participants and deafferented patients performed finger-tapping tasks either with or without visual and auditory feedback. While deafferented patients tended to anticipate the movement tapping far ahead of the pacing stimulus ( $-95$  ms) when visual and auditory feedback was not provided, healthy individuals showed asynchrony between their taps and the pacing signal around  $-30$  ms, indicating that they relied on proprioceptive and tactile information to control movement timing when no other feedback was available.

There is consistent evidence that tactile and kinesthetic information at finger–key contact is particularly relevant for timing accuracy of finger movements in music performance (Dalla Bella & Palmer, 2011; Furuya, Goda, Katayose, Miwa, & Nagata, 2011; Goebel & Palmer, 2008, 2013; Palmer, Koopmans, Loehr, & Carter, 2009). For instance, Goebel and Palmer (2008) found that pianists who presented maximum finger accelerations at finger–key contact showed an increased temporal accuracy for the temporal interval following the keystroke. Indeed, peak acceleration is directly associated with the amount of force applied, revealing the amount of tactile information available at the fingertip (Palmer et al., 2009). Therefore, this finding suggests that the availability of tactile feedback at key contact facilitates the planning and execution of upcoming events, hence increasing timing accuracy in performance. Palmer et al. (2009) extended these results in a study with a wind instrument. Skillful clarinetists performed melodies at different rates in a synchronization task while their movements were recorded with a motion capture system. The study found that performances containing more kinematic landmarks reduced timing error and that the magnitude of finger accelerations when making

initial contact with or releasing from the key surface was positively correlated with increased temporal accuracy during subsequent keystrokes. These results corroborate the notion that movement precision is associated in part with the amount of sensory (tactile) information available during the contact of the finger with the instrument.

There are also suggestions that proprioceptive feedback may be particularly relevant when performing at faster tempi (Dalla Bella & Palmer, 2011; Furuya et al., 2011; Goebel & Palmer, 2013; Loehr & Palmer, 2009; Palmer et al., 2009; Van Vugt, Furuya, Vauth, Jabusch, & Altenmüller, 2014). Dalla Bella and Palmer (2011) investigated the effect of performance rate on finger motion. Pianists performed melodies from memory at different rates while finger kinematics were recorded with a motion capture system to examine, for example, movement in the vertical dimension (height) perpendicular to the horizontal plane of the piano keyboard. It was reported that finger movement amplitude increased at faster performances, yielding greater finger heights above the keys. The authors suggested that a larger amplitude of motion at faster tempi may be a strategy used by performers to increase tactile and kinesthetic feedback at key-press to counter a speed-accuracy tradeoff and enhance temporal accuracy, allowing pianists to maintain high temporal accuracy when playing at faster tempi.

Studies have also shown that pianists use purposefully different types of touch (i.e., struck or pressed) during the performance to produce differences in dynamics and timbre (for review, see Goebel, 2017; MacRitchie, 2015). In the piano, for example, dynamics and timbre of isolated tones are controlled by the speed with which the finger interacts with the key surface, and consequently the velocity with which the hammer hits the strings (Goebel, Bresin, & Fujinaga, 2014; Goebel & Palmer, 2008). Different finger-key interactions induce distinct tactile feedback that is used by the musician to control the timing and sound quality during the performance (Goebel, Bresin, & Galembo, 2005; Goebel & Palmer, 2008; Hofmann & Goebel, 2016). In the Wöllner and Williamson (2007) study reported earlier, it was found that consistency in both expressive timing and intensity (dynamic) microstructure during the performance was highest in the conditions where kinesthetic feedback was provided and that the manipulation of this feedback input resulted in increased timing variability compared to the performance with normal feedback. However, it is important to note that the vast majority of research regarding the relevance of tactile feedback on music performance has been conducted with keyboard instruments; thus, further research is needed to examine the impact of tactile feedback on other instruments.

The effect of music training on tactile feedback processing has also been investigated to some extent (Kuchenbuch, Paraskevopoulos, Herholz, & Pantev, 2014; Ragert, Schmidt, Altenmüller, & Dinse, 2004). Kuchenbuch and colleagues (2014) presented short patterns of auditory and tactile stimuli with a tone-to-key relationship. Participants with various levels of music training heard sequences of five tones while receiving tactile stimulation to a finger corresponding to a specific note, mimicking the tactile and auditory interaction during music playing. Participants' task was to identify whether the stimulation pattern was congruent or incongruent, where congruent trials consisted of matches of audio-tactile stimulation on all five tones. The behavioral results suggested that musicians were better than nonmusicians at identifying incongruencies between audio and tactile mismatches. Imaging data acquired during the task revealed a clear influence of musical training on networks involved in audio-tactile integration with musicians showing increased activation in the premotor cortex and cerebellum than nonmusicians, corroborating the notion that multisensory stimuli are modulated by expertise (Gebel, Braun, Kaza, Altenmüller, & Lotze, 2013; Lotze, Scheler, Tan, Braun, & Birbaumer, 2003). Interestingly, areas associated with sensorimotor processing have been shown to be active in musically trained participants even during kinesthetic imagery and can be modulated



by the specific instrument of practice (Bangert et al., 2006; Bengtsson et al., 2005; Candidi, Sacheli, Mega, & Aglioti, 2014; Gebel et al., 2013; Lotze, 2013; Zatorre & Halpern, 2005).

Highben and Palmer (2004) tested the effects of two types of mental practice in learning to perform an unfamiliar piece. In the auditory-only practice condition, pianists read the music score while only listening to a computer-generated version of the music, whereas in the motor-only training musicians received somatosensory feedback from the piano keys but had no auditory feedback. In the “covert” practice condition, no auditory or movement-related feedback was available. Participants were asked to imagine the missing feedback information during practice. The results indicated that there was no significant difference between auditory or motor practice conditions in the number of notes recalled correctly when participants were asked to play the melodies from memory. However, participants who scored high on a post-test of aural skills were least disturbed in learning the piece without auditory feedback, suggesting that their auditory imagery skills facilitated learning.

## Implications for music education

The current state of knowledge summarized here provides evidence of the important role of sensory feedback on learning with relevant practical applications for contemporary music teaching and learning. In this section, we briefly highlight three main learning aspects that are facilitated by sensory feedback mechanisms and discuss some implications of the key research findings for music education practice.

Considering that music performance relies heavily on close action–perception interactions as each action in a music performance produces correlated perceptual outcomes (auditory, visual, somatosensory), a crucial aspect of learning is providing reliable sensory information that allows the system to form unbiased predictions and maintain accuracy and flexibility (Shadmehr et al., 2010). There is a growing body of research indicating that auditory (Bangert & Altenmüller, 2003; Drost et al., 2005; Lahav et al., 2007; Pfordresher & Chow, 2019; Pfordresher et al., 2011; Stewart et al., 2013), visual (Eldridge et al., 2010; Engel et al., 2012), and somatosensory feedback (Kuchenbuch et al., 2014) are important to integrate and consolidate a strong relationship between movements and their correlated perceptual outcomes, thus facilitating the development of sensorimotor representations necessary to build internal models (Altenmüller & McPherson, 2007). Therefore, music educators have an important role in ensuring that students understand the difference between effective and unproductive practices to prevent the consolidation of ineffective performance habits, particularly at the initial stages of skill acquisition. Action–perception associations emerge rapidly after minutes of training, and consistent practice strengthens the integration between movement and their predicted sensory outcomes (Bangert & Altenmüller, 2003; Baumann et al., 2007; Chen et al., 2012). Moreover, it has been shown that strong action–perception couplings may affect sensorimotor learning in face of new configurations (Pfordresher & Chow, 2019), corroborating the notion that providing reliable sensory information has an impact on future learning practices. Another aspect that one must consider regarding the development of close action–perception associations during learning is that the consolidation of the networks necessary for movement programming is rest- or sleep-dependent (Robertson, Pascual-Leone, & Miall, 2004). Thus, breaks between study sessions and an adequate amount of sleep are very important to reach a level of mastery in any musical repertoire (Altenmüller & Furuya, 2016). Indeed, research suggests that sleep seems to enhance musical performance by reducing the impact of proactive and retroactive interference of old information generated in past performances and preventing the loss of newly acquired information (Nusbaum, Uddin, Van Hedger, & Heald, 2018). Van Hedger,

Hogstrom, Palmer, and Nusbaum (2015) found that there is a functional dissociation between the mechanisms of consolidation for motor and conceptual learning as only conceptual errors (e.g., melodic interval, contour, chords) were significantly reduced after sleep. This study also demonstrated that both motor and conceptual errors increased over a 12-hr waking retention interval, again demonstrating the important role of rest or sleep for learning consolidation (see also Altenmüller & Furuya, 2016).

The literature reviewed here also indicates that sensory feedback facilitates learning of novel tasks. Specifically, research suggests that auditory feedback (Brown & Palmer, 2013; Engel et al., 2012; Lappe et al., 2018; Pau et al., 2013; Pfordresher, 2012) and visual information (Eldridge et al., 2010; Engel et al., 2012) significantly improve key-to-tone retention and consolidation for music beginners. The direct application of these findings in music education practice relates to the development and use of learning strategies to enhance sensory feedback awareness (Diedrichsen, White, Newman, & Lally, 2010; Taylor & Ivry, 2011). One technique that has been greatly applied in music teaching and learning makes the use of audio and video recordings of the student's performance to highlight aspects relating to sound quality and movement patterns during performance (Castellano, Bresin, Camurri, & Volpe, 2007; Riley, Coons, & Marcarian, 2005). More recently, researchers have examined the effectiveness of newly available technology to provide additional or extrinsic feedback with the end goal of enhancing performance (Anderson, Grossman, Matejka, & Fitzmaurice, 2013; Blanco & Ramirez, 2019; Brandmeyer, Timmers, Sadakata, & Desain, 2011; Furuya, Nakamura, & Nagata, 2014; Paney & Tharp, 2019; Pardue & McPherson, 2019; Sadakata, Hoppe, Brandmeyer, Timmers, & Desain, 2008; Timmers, Sadakata, & Desain, 2012). In general, findings suggest that providing real-time external feedback (visual or auditory) regarding timing accuracy (Timmers et al., 2012), finger movement (Furuya et al., 2014), singing accuracy (Paney & Tharp, 2019), pitch intonation in violin (Pardue & McPherson, 2019), and expressivity (Brandmeyer et al., 2011; Sadakata et al., 2008) can significantly benefit both music beginners and skilled performers (Anderson et al., 2013). This emerging area of applied research in music education and learning has a large potential, warranting further investigation of the promising application of additional/extrinsic sensory feedback in music practices.

Finally, evidence suggests that sensory information provided during learning can have significant impact on memory. The research reviewed here indicates that auditory information and active motor engagement facilitate memory (Brown & Palmer, 2012; Brown & Penhune, 2018; Engel et al., 2012; Finney & Palmer, 2003; Palmer, 2005; Pau et al., 2013; Schiavio & Timmers, 2016), while the independent role of visual and tactile feedback on memory remains unclear. Nonetheless, there is research showing that learning strategies that include multiple coding forms (visual, auditory, tactile, and kinesthetic) facilitate later retrieval (Petrini et al., 2009; Wan & Schlaug, 2010), promote the development of mental imagery (Highben & Palmer, 2004; Lotze, 2013; Zatorre & Halpern, 2005), and enhance the overall learning experience (Riley et al., 2005). These findings thus indicate that, although the research reviewed here focuses on the individual role of auditory, visual, and somatosensory feedback mechanisms on learning and performance, it is important to consider the role of sensory feedback integration on music teaching and practice (Zimmerman & Lahav, 2012).

## Conclusion

This review examined a growing body of research to better understand how and to what extent sensory feedback mechanisms influence musical learning and performance, addressing particularly the interaction between musicians and their instrument. The current state of

knowledge overviewed here provides consistent evidence that auditory (Konvalinka et al., 2010; Mates et al., 1992; Nowicki et al., 2013; Schultz & Palmer, 2019) and somatosensory feedback mechanisms (Aschersleben et al., 2001; Dalla Bella & Palmer, 2011; Furuya et al., 2011; Goebel & Palmer, 2008; Palmer et al., 2009) play a crucial role in the control of timing and movement sequencing in sensorimotor synchronization. Ensemble cohesion and interpersonal coordination during music performance greatly rely on the availability of auditory (Goebel & Palmer, 2009; Konvalinka et al., 2010; Mates et al., 1992; Nowicki et al., 2013; Schultz & Palmer, 2019) and visual information between co-performers (Bishop & Goebel, 2015, 2018; D'Amario et al., 2018; Goebel & Palmer, 2009; Palmer et al., 2019). Finally, studies also show that although the absence of auditory feedback (Bishop et al., 2013; Finney & Palmer, 2003; Highben & Palmer, 2004; Repp, 1999) or visual input (Wöllner & Williamon, 2007) has negligible effects on the performance of well-known and memorized musical pieces, delayed feedback and content perturbation of the auditory feedback can significantly disrupt the fluency of production by affecting movement timing and accuracy, respectively (Pfordresher & Dalla Bella, 2011; Pfordresher & Kulpa, 2011; Pfordresher & Palmer, 2006). Regarding learning, the current literature suggests that sensory feedback is crucial for the consolidation and integration of action–perception couplings (Bangert & Altenmüller, 2003; Drost et al., 2005; Eldridge et al., 2010; Engel et al., 2012; Kuchenbuch et al., 2014; Lahav et al., 2007; Pfordresher & Chow, 2019; Pfordresher et al., 2011), learning a novel task (Brown & Palmer, 2013; Eldridge et al., 2010; Engel et al., 2012; Lappe et al., 2018; Pau et al., 2013; Pfordresher, 2012), and can also impact memory and mental imagery (Brown & Palmer, 2012; Brown & Penhune, 2018; Engel et al., 2012; Palmer, 2005; Pau et al., 2013; Schiavio & Timmers, 2016; Zatorre & Halpern, 2005).

Despite the many advances on this topic, some issues regarding the role of sensory feedback mechanisms on music performance and learning remain elusive. It is of note that the vast majority of the literature on sensory feedback mechanisms in music is based on studies with keyboard instruments, raising the question of whether much of what we know on this topic applies to other instruments or singing. It is also evident that studies have focused significantly on understanding the role of auditory feedback mechanisms; thus, more research is needed to better understand the impact of other sensory mechanisms on performance and learning. Further research on the effects of working memory and musical imagery in the context of altered sensory feedback, possible individual differences and instrument expertise, and the implications of augmented feedback to enhance learning and performance are topics for future research on the effect of sensory feedback in music performer–instrument interactions.

Overall, this growing body of research provides extensive evidence of the role of feedback mechanisms, sensorimotor integration, and action–perception coupling for learning and production fluency in music performance, with important implications for education as it impacts the development of evidence-based learning strategies and opens the possibility of using technology-based techniques to improve learning and performance.

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