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Perceptions of discrepancies between intentions and outcomes during music practice: Differences among musicians with varied levels of experience and expertise

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Perceptions of discrepancies between intentions and outcomes during music practice: Differences among musicians with varied levels of experience and expertise

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Perceptions of discrepancies between intentions and outcomes during music practice: Differences among musicians with varied levels of experience and expertise

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Errors are an inherent and necessary part of learning in all dimensions of human activity. In order to effectively encode and refine procedural memories, learners must experience attempts to accomplish goals, perceive discrepancies between the results of their attempts and their intended outcomes, and adjust their behavior to accommodate those discrepancies. The extent to which music practice results in positive changes in the quality of performance and extent of performers' facility is in part a function of the precision of learners' physical and auditory goals and learners' discrimination of discrepancies between those goals and the outcomes their movements produce.

We designed three experiments to examine musicians' perceptions of their own others' practice. In Experiment 1, immediately after recording individual practice sessions, high school, college, and professional musicians listened to their recordings and pressed a computer key to mark moments of discrepancy between what they had intended while practicing and what they heard on the recordings; in Experiment 2, the high school and professional participants from Experiment 1 repeated the task 2 years later; in Experiment 3, high school and professional participants heard practice recordings of four other violinists' practice (two artist-level experts and two competent students), and pressed the key each time they heard a discrepancy between what they heard on the recordings and what they would have intended had they been the practicer.

In Experiment 1, the mean rates of keypresses did not differ among the high school, undergraduate, graduate, and professional participants, although there were large within-group variances. When the high school and professional participants in Experiment 1 returned after 2 years and performed the same task with their original recordings, high school participants marked significantly more discrepancies, but the mean rate of keypresses among professionals did not increase. In Experiment 3, professionals marked significantly more discrepancies than did high school participants, but and the mean rates of keypresses within each group did not differ among recordings by professionals and high school musicians. These results are consistent with the notion that the precision of performance goals and the acuity of perceptual discrimination are central features of musical expertise.

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Chapter I: Introduction and Review of Literature

Errors are an inherent and necessary part of learning in all dimensions of human activity. In order to effectively encode and refine procedural memories (i.e., memories of how to do things), learners must experience attempts to accomplish goals, perceive the discrepancies between the results of their attempts and their intended outcomes, and adjust their behavior to accommodate those discrepancies (Herzfeld & Shadmehr, 2014; Seidler, Kwak, Fling, & Bernard, 2013; Wu, Miyamoto, Castro, Ölveczky, & Smith, 2014). This broad view of error in learning encompasses instances in which ongoing behavior is amenable to adjustments during the course of action (balancing on a bicycle or adjusting the pitch of a sustained tone in music) and instances in which errors are uncorrectable once the target behavior is executed (pressing a key on a computer or playing a pizzicato chord on a violin).

It seems that many novice music learners conceive of errors only as discrete events, not realizing perhaps that nearly all movements that unfold over time involve ongoing adjustments intended to reach discernible goals with increasing precision. Discussions about performance quality often frame errors in terms of their discrete consequences (falling off a bicycle, playing a note out of tune), which does not acknowledge the motor system's use of an ongoing feedback loop capable of updating motor commands both during movement and in future attempts (Chen, Woollacott, & Moore, 2013; Katahira, Abla, Masuda, & Okanoya, 2008).

What varies among the performances of novices and experts is often more than simply the number of errors that occur, but how quickly adjustments are made that render errors imperceptible to observers, thus avoiding the negative consequences (Chen, Woollacott, Pologe, & Moore, 2008; Kruse-Weber & Parncutt, 2014). Chen and colleagues (2008, 2013) precisely examined expert cellists' finger movements as the cellists shifted their left hands along the fingerboard of the instrument and observed that cellists made small positional changes in finger shape after initial contact with the string, ostensibly to correct the resulting pitch (Chen et al., 2008). Cellists who demonstrated higher perceptual ability regarding pitch also demonstrated higher performance accuracy in their shifting motions. Experienced cellists who performed familiar shifting patterns were more accurate executing shifts together with the bow (i.e., shifting between sustained, bowed tones) than shifts without the bow. Taken together, these findings indicate that string musicians sample the auditory effects of their movements and make physical adjustments moment to moment.

Neurophysiological investigations have shown that skilled musicians with extensive training can correct or minimize errors even before the auditory onset of an errant note (Maidhof, 2013; Ruiz, Jabusch, & Altenmüller, 2009; Ruiz, Strübing, Jabusch, & Altenmüller, 2011). Maidhof and colleagues (2009) demonstrated that skilled pianists perceive upcoming errors prior to the onset of auditory feedback. Changes in brainwave potentials (event-related potentials, or ERPs) indicate that detection of error in rapid movement sequences actually *precedes* the performance of keypress errors, and that incorrect keypresses are performed slightly later and more softly (slower key velocity) than correct keypresses. These neurological data are consistent with behavioral observations of music practice, which indicate that experts often stop or slow down in anticipation of potential errors (Duke, Simmons, & Cash, 2009).

In this dissertation, we define errors as moments of discrepancy between movement goals (intentions) and outcomes, a definition consistent with literature examining errors in procedural memories (Shadmehr, Smith, & Krakauer, 2010). This definition also has important implications for skill learning in music, as the clarity of a performer's intentions necessarily determines the performer's self-perceptions of accuracy in fulfilling those intentions. If, for example, a young musician's proximal goal is to *remember the c-natural* in a brief exercise, his perception of accuracy will depend primarily on whether he actually played the correct pitch (or an approximation of the correct pitch). In contrast, a musician whose goal it is to beautifully connect the c-natural to the note that follows will base her perception of accuracy not only on playing the correct pitch, but also on aspects of articulation and inflection that may not be a part of novices' thinking. Failing to meet the intended goal in either case may be considered an error by the learner, again in the sense that there is a discrepancy between the performers' intentions and outcomes, but the more experienced musician will perceive discrepancies between what she is doing and this more precise and elaborate goal.

THE BIOLOGICAL LOGISTICS OF MOVEMENT

Motor movements are conceived in the central nervous system (CNS) and executed when charged ions move across neuronal membranes, altering neurons' electrical potentials and producing electrical impulses. When the correct motor neurons fire, a motor command travels down axons in the spinal cord toward nerves within the muscle fibers that initiate contraction (Wolpert & Ghahramani, 2000).

Motor commands activate motor primitives, or small coordinated groups of muscle movement (synergies) that can be combined at different proportions with other primitives to form more complex movements (Giszter, Mussa-Ivaldi, & Bizzi, 1993). Researchers have proposed that individual neurons encode information about the direction of movement, velocity, acceleration, posture, or joint turning force (torque) (Georgopoulos, 1995; Kakei, Hoffman, & Strick, 1999; Mussa-Ivaldi, 1988; Sanger, 1994; Scott & Kalaska, 1995).

During intentional movements, afferent nerves in the sensory system relay tactile and proprioceptive information back to the CNS. Proprioceptive feedback, information about where limbs are in space, is intrinsic to all movements, and for many movements, learners receive visual, auditory, olfactory, haptic, or gustatory feedback as well. Over time, this feedback becomes coupled with movements, which leads to the development of expectations about movement outcomes.

The sensory system updates and corrects the motor system as movements unfold and during future iterations, a description supported by psychological (Prinz, 2013), computational (Wolpert & Ghahramani, 2000; Wolpert & Kawato, 1998), neurophysicological (Rizzolatti & Craighero, 2004; Rizzolatti & Sinigaglia, 2010), and behavioral research (Sober & Brainard, 2009). The CNS relies on afferent signals from the sensory system to inform efferent signals from the CNS in what becomes a sensorimotor feedback loop that both controls and evaluates motor movements as they occur.

Effective motor control requires that the sensorimotor system overcome two main challenges: to accommodate noise and delay in afferent signals from the sensory system (Wolpert & Ghahramani, 2000), and to produce highly variable motor commands that are appropriate given the initial state, the movement objective, and the environment. Motor commands and afferent sensory information travel along axons slower than the speed of sound, and neurons within the CNS take tens of milliseconds to complete their role (Shadmehr, Smith, & Krakauer, 2010).

Interesting investigations into these processes have been designed to study movements of the eyes, which make frequent ballistic movements, called saccades, between consecutive points of focus (fixations). These eye movements last less than 80 ms, with the eyes traveling more than 400 deg/s (Shadmehr et al., 2010), too rapidly for the CNS to receive proprioceptive or visual feedback from the sensory system. Saccades move the eyes between fixation points that may be located anywhere in the visual field, which requires highly variable motor commands. Saccades occur with greater velocity when participants are asked to look at a target (fixed goal) than when they are asked to look away from a target (Smit, Van Gisbergen, & Cools, 1987) or if the reward for looking at a target is increased (Takikawa, Kawagoe, Itoh, Nakahara, & Hikosaka, 2002). The velocity of saccades is also increased if the saccades are accompanied with the movement of a limb (Snyder, Calton, Dickinson, & Lawrence, 2002; van Donkelaar, 1997) or if the visual target is repositioned during the saccade (Xu-Wilson, Chen-Harris, Zee, & Shadmehr, 2009). The CNS must create motor commands that accurately execute saccades with different velocities depending on the goals and state of the subject and the environmental conditions (Shadmehr et al., 2010).

In the 1970's, Robinson suggested that to overcome the challenges inherent in motor control, the CNS creates an internal representation of the expected sensory outcomes of a given motor command (Robinson, 1973), termed the efference copy, that is encoded in a corollary discharge within the CNS. Although motor commands produce sensory feedback in the physical world, Robinson posited that the CNS generates an internal representation of the expected sensory consequences of a given movement.

By making predictions about the *expected* sensory consequences of movements and simultaneously assessing the *actual* sensory consequences as movements unfold, the CNS compares these two streams of information. When there is a discrepancy between the predicted sensory feedback and the actual feedback, the CNS registers a prediction error and is better poised to accommodate that error. This model of motor control, termed the forward internal model or the feedforward system of motor control, has been systematically studied using behavioral, computational, and neurophysiological methods.

Motor learning literature consistently defines errors as moments of discrepancy between movement goals (intentions) and outcomes. This broad definition includes moments when actions require ongoing adjustments (keeping a car between the lanes of a highway, adjusting the bow weight during a sustained tone) and discrete instances in which errors are uncorrectable once the target behavior is executed (pressing a key on a computer or playing a pizzicato chord during a recitative).

Behavioral Evidence

Studies examining the behavioral outcomes of motor movements offer support for a feedforward system of motor control mediated by error perception, providing evidence that the motor system utilizes two lines of information to generate accurate motor commands: sensory feedback and sensory predictions. To study this further, researchers manipulate participants' perceptions of their motor movement and look for evidence of learning from this manipulated state.

Sober and Brainard (2009) examined this phenomenon by investigating adult song birds. While still juveniles, Bengalese finches learn songs composed of distinct phonemes at set pitch intervals. The birds develop a clear, crystalized mental model of how the song should sound during adolescence, and the birds continue to sing at these frequencies throughout their adult lives (Ölveczky, Andalman, & Fee, 2005). Sober and Brainard fit adult birds with specially designed headphones through which the birds listened to themselves singing in real-time. As the birds sang, the researchers altered the frequency of a series of tones embedded in the middle of the birds' songs so the birds heard through their headphones frequencies other than those they actually produced.

While listening to the mismatched auditory output, the birds adjusted the production of their song so that they would hear a version through the headphones that matched their crystalized auditory model. To an outside observer, the birds were singing a half-step sharp or flat during the altered segment, but through the headphones, these incorrect notes sounded at the original pitch due to the auditory manipulation.

In this task, the researchers manipulated the birds' auditory feedback, but they did not manipulate the birds' perceptions of the goal. The birds maintained a clear internal model of their song, and they modified their motor commands to produce a song that, according to their own perception, matched that internal model. When the birds perceived a discrepancy between what they expected to hear and what they were actually hearing, they moderated their motor commands to adjust for the discrepancy. When the sensory feedback did not match the sensory prediction, the motor system adjusted.

After the birds practiced for two weeks in a manipulated sensory feedback loop, Sober and Brainard stopped transposing pitches within the song and the birds heard what they were actually singing. Since these pitches had been drawn a half-step sharp or flat due to two weeks of manipulated practice, the birds again modified their motor commands to correct the pitches. After two weeks of practicing a procedural memory that produced incorrect tones, the birds were able to modify their motor system to produce the accurate pitches again, reflecting the high degree of flexibility in motor control.

Recent research in motor learning suggests, contrary to some commonly held beliefs, that learners who experience error making and manage errors during self-directed active practice perform better than do learners who avoid errors during the learning process (Heimbeck, Frese, Sonnentag, & Keith, 2003; Huang, Shadmehr, & Diedrichsen, 2008; Keith & Frese, 2005; Wills, Lavric, Croft, & Hodgson, 2007); for meta-analysis of error management training, see Keith and Frese (2008).

Variability early in motor learning provides opportunities for learners to build associations between their movements and outcomes (Herzfeld & Shadmehr, 2014).

Environments that allow iterative attempts at accomplishing goals and, in close temporal proximity, feedback about outcomes provide opportunities for motor skill learning to occur. Once associations are created, learners can exploit what they know to accomplish intended goals.

A recent investigation that observed participants practicing a reaching task demonstrates the value of early task-related variability. Wu, Miyamoto, Castro, Ölveczky, and Smith (2014) asked participants to manipulate a lever attached to an arm in an effort to move the arm along a target trajectory. Greater task-relevant variability during the early stages of learning predicted faster learning once the target trajectory was refined. This was demonstrated in both reward-based and error-based paradigms. Early variability, which produced greater movement error, was not detrimental to learning, but instead predicted faster learning.

COMPUTATIONAL STUDY OF MOTOR CONTROL

During the 1960's, Kalman developed a process of mathematical prediction that combined two streams of information unequally (Kalman, 1960) in an effort to apply more weight to the stream of information considered to be more reliable and minimizing potential error in the resulting estimate. This algorithm, now known as the Kalman filter, applies a Bayesian process, which formulates predictions incorporating both prior belief (prediction) and current evidence (sensory feedback), weighing each source of information dependent upon the noise within the sample (Meyniel, Sigman, & Mainen, 2015; Shadmehr et al., 2010).

When Robinson (1975) proposed that the CNS relied on a feedforward mechanism to detect errors, the Kalman filter was already being studied and refined. Researchers began hypothesizing that a Kalman filter could represent mathematically the process by which the motor system makes comparisons between efferent predictions and afferent sensory feedback, weighting these variables with regard to uncertainty, and subsequently updating motor commands.

The model of this process posits that as movements unfold, the state (position, velocity, torque, and balance of the limbs) changes rapidly and continuously, and typically the context (the item the limb is moving, the weight of the limb itself) remains stable. An accurate motor command must be well suited to both the state and the context of the movement, and the accuracy of the command is dependent upon the accuracy in predicting the current and future states within a given context (Wolpert & Ghahramani, 2000). As explained above, the CNS generates a motor command based upon what is known about the current state and context and simultaneously generates an efference copy, encoding predicted sensory feedback. The CNS then makes ongoing comparisons between the afferent feedback and the efference copy. Discrepancies between what was expected and what is experienced signals a prediction error, which updates the motor command through a process mathematically represented by the Kalman filter.

Wolpert and Ghahramani described this process as comprising three stages (Wolpert & Ghahramani, 2000). During the first stage, the CNS assesses the current state and context using afferent sensory information (Eskandar & Assad, 1999; Kim & Shadlen, 1999) and constructs an Inverse Model that transforms states along the desired trajectory into motor commands (Kawato, Furukawa, & Suzuki, 1987; Wolpert & Ghahramani, 2000). This also produces an efference copy representing the predicted haptic feedback encoded in the corollary discharge.

During the second stage, termed the Forward Dynamic Model stage, the CNS evaluates how the state changed relative to the motor command by comparing the expected sensory feedback to the actual sensory feedback. During the third stage, termed the Forward Sensory Model, the CNS creates an updated internal representation of the current state given the information learned in the comparison of the expected sensory feedback and the actual sensory feedback (Wolpert & Ghahramani, 2000).

To update or refine a procedural memory, the motor system relies on a comparison of expected and actual sensory feedback. The standard model of motor learning (Herzfeld & Shadmehr, 2014; Thoroughman & Shadmehr, 2000) mathematically represents this process. For trial η, and perturbation χ, imposed on action μ, the sensory consequences γ are

$$\gamma^{(\eta)} = \mu^{(\eta)} + \chi^{(\eta)}$$

A learner's belief about the current state and context, $\check{\chi}^{(\eta)}$, informs her prediction of the sensory consequences stored in the efference copy,

$$\check{\gamma}^{(\eta)} = \mu^{(\eta)} + \check{\chi}^{(\eta)}$$

If there is a prediction error,

$$e^{(\eta)} = \gamma^{(\eta)} - \check{\gamma}^{(\eta)}$$

she updates her belief dependent upon a decay factor α and error sensitivity ε.

The information used to generate a future motor command will be a product of the current belief about the environment moderated by a decay factor and the updated belief about the environment moderated by error sensitivity, expressed mathematically as,

$$\check{\chi}^{(\eta+1)} = \check{\alpha}^{(\eta)}\chi^{(\eta)} + \epsilon^{(\eta)}e^{(\eta)}$$

The model takes into account the certainty of the measurement, relying less on efference copies or sensory feedback signals that contain noise by weighing error information inversely to the degree of variability within the error information sample. As learners refine skills, discrepancies between intentions and actual sensory outcomes result in prediction errors that alert the motor system to update the movement structure.

NEUROPHYSIOLOGICAL CORRELATES OF MOTOR CONTROL

Investigations into the neurophysiological correlates of procedural skills have found evidence in support of this feedforward, error-related neuronal processing. Electroencephalogram (EEG) recordings measure the electrical impulses that originate within the brain through the use of carefully placed electrodes along the scalp. EEGs record brainwaves with great temporal precision, but they are much less accurate in determining the spatial origin of electrical signals within the brain.

Early investigations reported a sharp negative deflection 50-100 ms after incorrect responses during speed choice reaction time tasks (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Coles, Meyer, & Donchin, 1990; Gehring, Goss, Coles, Meyer, & Donchin, 1993). During these tasks, a stimulus is displayed on either the right or left side of a computer screen, and participants are asked to respond by pressing a key on the corresponding side of the keyboard as quickly as possible. Since participants are forced to make choices quickly, they produce occasional response errors that are easily and immediately recognizable by the participant.

Waveforms recorded through EEG revealed a more negative deflection after erroneous responses when compared to waveforms recorded after correct responses. This negativity was termed both error negativity (Ne) (Falkenstein et al., 1991) and error related negativity (ERN) (Gehring et al., 1990, 1993). Several authors have confirmed that both the Ne and the ERN have the same shape, latency, amplitude, and scalp distribution, and it is now assumed that they are the same event (Bernstein, Scheffers, & Coles, 1995; Nieuwenhuis, Holroyd, Mol, & Coles, 2004). ERN is created after incorrect responses regardless of the modality in which the stimulus is presented (Falkenstein, Hoormann, Christ, & Hohnsbein, 2000) and regardless of whether the response is made by hand or foot (Holroyd, Dien, & Coles, 1998).

The ERN response has also been found after errors produced during go/no-go tasks (Scheffers, Coles, Bernstein, Gehring, & Donchin, 1996). Similar to the choice reaction time tasks, go/no-go tasks again show stimuli that correspond with a key on the left or the right side of a computer keyboard. These stimuli are either green, which indicates to the participant that she should respond with a keypress on the corresponding side, or red, which indicates to the participant that she should inhibit her response. ERN was observed on trials in which the participant responded to a green stimulus by pressing a key on the incorrect side and also for trials in which the participant erroneously pressed a key during a red signal.

Pressing the incorrect key on a green signal can be corrected through on-going adjustments. Participants can, and often do, correct errors by pressing the key on the opposite side immediately after the erroneous press. Pressing a key on a red signal cannot be corrected once the motion is executed. This discrete error event is executed in a fast single motion, and pressing an additional key would multiply the number of errors.

Both types of errors can similarly be observed within a musical context. On a bass, shifting to a sustained note and landing flat can be corrected with an extra push of the hand and finger, and sometimes even disguised within a vibrato motion, all within the time that the note is sustained. Plucking a pizzicato chord during a recitative cannot be undone or adjusted once the motion has been executed, and any additional attempts would produce additional, audible errors.

ERNs were present after errors in which participants immediately tried to correct their actions, and also after errors in which participants could not (and did not try to) correct their actions. If the ERN was the result of an error correction process, rather than an error detection process, one would expect ERNs to only be present when the error was being corrected. Instead, it seems the error correction process is not necessary to elicit an ERN (Scheffers et al., 1996).

The ERN begins at or slightly before the error response, and peaks around 50-100 ms later (Maidhof, 2013). This latency is consistent regardless of how the response stimulus is presented to the participants, and regardless of the modality in which participants respond to the stimulus (Bernstein et al., 1995; Falkenstein et al., 1991, 2000; Gehring et al., 1993; Maidhof et al., 2009; Maidhof, Vavatzanidis, Prinz, Rieger, & Koelsch, 2010; Scheffers et al., 1996).

The exact latency between the erroneous response and the onset of the ERN is very consistent within individual studies, though there is a great deal of variation between studies (Maidhof, 2013). Different investigations within the literature have measured the timing of the waveform from both the onset of muscle movement as measured by an electromyogram (EMG) and from the moment a response key has been completely depressed. Maidhof suggests that this may account for some of the variation in latency. The ERN appears later in waveforms that are time-locked to the onset EMG activity than in waveforms time-locked to the closing of the key switch circuit. Further variations in the latency reported by individual studies could also be explained by variability in the travel time of a response key to become completely depressed (Kappenman & Luck, 2011; Maidhof, 2013).

The EEG electrodes that most easily measure the ERN are located at midline frontocentral scalp locations, most typically those labeled Fz, FCz, and Cz (Maidhof, 2013). The ERN likely originates in the rostral portion of the anterior cingulate cortex (ACC) and may also involve portions of the left lateral frontal cortex (Herrmann, Römmler, Ehlis, Heidrich, & Fallgatter, 2004; Kiehl, Liddle, & Hopfinger, 2000; Ridderinkhof et al., 2004). The ACC is positioned adjacent to the corpus callosum on the medial surface of the frontal lobe; the rostral portion of the ACC is the section positioned toward the forehead. The ACC is thought to be involved in cognitive control and the processing of both novel and error events (Ridderinkhof et al., 2004; Van Veen & Carter, 2002).

The location of the signals emanating from the ACC has been inferred from EEG data using the electrophysiological source localization method (LORETA) (Herrmann et al., 2004), which triangulates the origin of an electric charge within the brain in a way that is similar to how seismologists triangulate the epicenter of an earthquake. Since EEG data are not topologically precise, researchers have also used functional magnetic resonance imaging (fMRI) data to confirm the findings (Debener et al., 2005; Holroyd, Nieuwenhuis, Mars, & Coles, 2004). This method allows researchers to observe differences in blood flow within the brain; it is very accurate with spatial measurements, but less accurate in temporal measurements.

There are several theories about the functional role of the ERN. The feedforward model posits that the ERN is activated by a discrepancy between the neural representation of the correct response and the neural representation of the actual response within the learners' CNS (Bernstein et al., 1995; Desmurget & Grafton, 2000; Falkenstein et al., 2000; Ruiz et al., 2009; Scheffers et al., 1996; Wolpert, Ghahramani, & Jordan, 1995). Proponents of this theory suggest that as learners perform a specific action, they have an internally derived model of what they expect to happen which is then compared to the actual outcome. Once an error is perceived, the motor system can respond by either inhibiting or correcting an erroneous response. The theory posits that discrepancies can occur after quick motions that produce discrete errors (such as a pizzicato chord played at the wrong time during a recitative), or as part of ongoing action-monitoring during events that unfold over time (such as adjusting the pitch of a sustained tone).

The feedforward theory is supported by several key findings. A negativity that is similar to the ERN, but smaller in amplitude, is present after correct responses, which suggests that the negativity after both correct and incorrect responses could represent the comparison process itself, rather than the actual outcome (Falkenstein et al., 2000; Vidal, Hasbroucq, Grapperon, & Bonnet, 2000). The magnitude of the ERN is dependent upon the similarity or dissimilarity between the actual response and the intended response (Bernstein et al., 1995), though more recent data suggest that this may not always be true (Steinhauser & Yeung, 2010). The intent and motivation of participants can also influence the amplitude of the ERN. Participants instructed to focus on accuracy above speed produced enhanced ERNs as compared to participants focusing on speed above accuracy (Scheffers et al., 1996).

Though the feedforward model is currently the most supported theory, two other hypotheses about the role of ERN have yet to have been excluded (Maidhof, 2013). The conflict monitoring theory posits that ERN is elicited when two competing response representations are activated (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Carter et al., 1998; Van Veen, Cohen, Botvinick, Stenger, & Carter, 2001). Once an error has been detected, learners can respond with multiple actions. The neural representation of these choices could result in dual activation, which requires an inhibition response for at least one of the response options. Inhibited responses could also occur during correct responses, which could explain why a negativity similar to the ERN but smaller in magnitude, is also observed after correct responses.

At earlier stages of learning, when performance is poor and participants have weaker internal models of what constitutes accurate performance, there is a larger ERN than in later stages of learning (Padrão, Penhune, de Diego-Balaguer, Marco-Pallares, & Rodriguez-Fornells, 2014). This theory posits that novice learners, still unsure about how to correct an erroneous response, many have a stronger conflict between competing motor responses attempting to correct the error. As participants gain experience and develop stronger couplings between their actions and the consequences of their actions, a smaller ERN can be seen because erroneous events may elicit fewer competing models for correction (Padrão et al., 2014). However, participants who demonstrate errors in a go/no-go paradigm show no difference in the magnitude of ERN when producing an error that could be corrected through an inhibitory response and errors that could not be corrected, suggesting the ERN is more likely related to the detection process than the inhibitory process (Scheffers et al., 1996).

Another hypothesis about the role of the ERN is that it is the product of an outcome that is perceived as being worse than the outcome expected by learners. Holroyd and Coles (2002) suggest that the dopaminergic pathways within the midbrain generate a negative charge that is then conveyed to the ACC as a means to modify both future and current performances. This theory posits that the ERN is a product of the emotional response to an error which can be observed through an affective influence on the amplitude of the ERN (Luu, Flaisch, & Tucker, 2000; Luu, Tucker, & Makeig, 2004).

The ERN is followed by a positive deflection termed the positive charge (Pe); for review see Overbeek, Nieuwenhuis, and Ridderinkhof (2005). Unlike ERN, which originates in the rostral area of the ACC, the Pe likely originates from the caudal area of the ACC (Van Veen & Carter, 2002). The amplitude of the Pe is typically larger when participants are consciously aware of an erroneous response (Endrass, Reuter, & Kathmann, 2007; Nieuwenhuis, Ridderinkhof, Blom, Band, & Kok, 2001; Overbeek et al., 2005). This is not true for the ERN, which has a similar magnitude regardless of whether the error is consciously perceived (Nieuwenhuis et al., 2001). As summarized by Orr and Carrasco (2011), "The ERN reflects evidence that an error has occurred, whereas the Pe reflects the process that decides that an error has just occurred" (p. 5891).

A study by Steinhauser and Yeung (2010), however, produced results that were somewhat inconsistent with these findings. They observed a relationship between the magnitude of the Pe and the strength of accumulated evidence a learner possesses that an erroneous response has been produced. They suggest that the Pe is more directly correlated with the error detection processes than with the conscious recognition process. The Pe could be measuring a relationship between a participants' ability to recognize an error, the error's salience, and the consolidation of an internal model (Padrão et al., 2014).

Though the error awareness hypothesis continues to be the most widely supported hypothesis about the functional significance of the Pe, two other possibilities have not been excluded. One alternative hypothesis posits that this neurological event may be related to the behavior-adaptation process, which facilitates learners' responses to erroneous results by initiating a remedial performance or ongoing adjustments (Hajcak, McDonald, & Simons, 2003). This could possibly explain the post-error slowing during complex procedural memory tasks (Rabbitt, 1978; Ruiz et al., 2011; Strübing, Ruiz, Jabusch, & Altenmüller, 2012).

Yet another hypotheses about the nature of the Pe suggests that it reflects an affective response to errors, which can occur along with biological changes in heart and respiration rates (Falkenstein et al., 2000; Maidhof et al., 2009; Overbeek et al., 2005; van Boxtel, van der Molen, & Jennings, 2005).

A positive charge similar to the Pe, termed the P300, is also observed following surprise or novel events. The Pe and P300 might represent related neuronal processes

(Overbeek et al., 2005; Ridderinkhof, Ramautar, & Wijnen, 2009), which furthers the notion that the ERN and the N2 ERP (a novelty related response similar to the ERN) involve a related or shared neural network (Wessel, Danielmeier, Morton, & Ullsperger, 2012); for a review see Polich (2007).

Error Related Potentials During Music Performance

Several studies have examined the neurological correlates of errors during music performance. These include several studies of ERPs recorded from expert pianists while they performed standard piano literature (Ruiz et al., 2009, 2011; Strübing et al., 2012) and scales and fingering patterns (Maidhof et al., 2009, 2010).

The participants in these studies wore EEG caps to record the brain potentials along their scalp while they played on MIDI equipped keyboards that recorded the auditory onset of the notes they played. Participants were blindfolded to prevent them from receiving visual feedback from their hands or the keys, and were asked to perform at fast tempos so that they would be more likely to commit fingering errors. The durations of the inter-onset interval between notes (IOI) ranged from 125 to 360 ms (approximately 32nd notes to triplets at 60 bpm), fast enough to induce speed related errors even in expert players.

Under these conditions, several main findings emerged. In addition to the post-ERN, a negative event related potential occurred 100 ms before the onset of auditory feedback (Maidhof, 2013; Ruiz et al., 2009; Strübing et al., 2012). Differences between correct and erroneous responses were observed in the brainwaves of skilled pianists before they fully depressed the piano key. This pre-error related negativity (pre-ERN) suggests that there is a mechanism by which skilled pianists, without conscious awareness, compare internal goals with predicted consequences in a feedforward model

(Maidhof et al., 2009). It also suggests that skilled pianists generated an error signal prior to the auditory onset of the wrong notes, indicating that they were about to produce an error.

Similar to the ERN, the pre-ERN likely originates in the rostral part of the ACC (Ruiz et al., 2009), which is consistent with data that suggests this region is utilized during error-related processes (Ridderinkhof et al., 2004). Errors committed in just one hand during bimanual performances have no lateralization effects in the event related potentials preceding or following erroneous responses. This suggests that the pre-ERN is likely part of the cognitive error detection process, and not part of the low-level motor-related processes where a lateralization effect would be expected (Maidhof et al., 2009).

The tempo at which the performers executed the keypresses influenced the variability of latency times for the pre-ERN. IOIs around 360 ms (approximately triplets at 60 bpm) elicited pre-ERNs around 150-180 ms prior to the auditory onset (Maidhof et al., 2009); IOIs around 125 ms (approximately 32nd notes at 60 bpm) produced pre-ERNs 70-20 ms prior to the auditory onset (Ruiz et al., 2009, 2011; Strübing et al., 2012).

Maidhof (2013) suggests that the latency differences could be explained in two different ways. With the slower tempi, error detection and correction could begin at an earlier stage since there is more time to prepare, initiate, and execute each keypress. Or, there could be an artifact effect of the ERP analyses. If ERPs of erroneous keypresses overlap with the ERPs of the previous notes, tempo differences could also cause latency differences in the total amplitude resulting from this overlap. However, studies capable of differentiating overlapping brain signals suggest that the pre-ERN is not likely to be due to an ERP artifact (Ruiz et al., 2009).

The MIDI keyboards also recorded both the keypress velocity and the inter-onset intervals (IOI) between notes. The data that were collected from the MIDI system indicate that there were behavioral responses to errors. Erroneous keypresses were executed with less velocity than were the same keypresses performed correctly at other points during the piece (Ruiz et al., 2009, 2011; Strübing et al., 2012) or performed in the opposing hand (Maidhof et al., 2009). When pianists executed an erroneous keystroke in one hand while performing the same note pattern correctly in the other hand at a different octave, they demonstrated slowed velocity in the erroneous hand but not in the hand executing the passage correctly (Maidhof et al., 2010).

Erroneous keystrokes were also executed with a slower IOI measured from the previous note to the erroneous note, termed "pre-error slowing" (Maidhof et al., 2009; Ruiz et al., 2009, 2011; Strübing et al., 2012). Similarly, the IOI from the erroneous note to the following note was also expanded in what was termed "post-error slowing." Highly trained pianists have been observed slowing or stopping in anticipation of errors during practice (Duke et al., 2009), and this could be the mechanism through which this is possible. When performing bimanually, pianists who produced an error in just one hand performed that note with a longer IOI in both hands. Velocity changes were seen in only one hand, but tempo fluctuations were observed in both hands. Delaying the timing of both hands thus avoided moments of asynchrony between the hands and would render the error less noticeable than delaying the timing of just one hand.

These findings about skilled pianists are consistent with the findings of behavioral studies of skilled typists. Expert typists produced erroneous keypresses that were both less forceful and slower than correct responses, suggesting that there is a mechanism by which skilled typists, without conscious awareness, detect discrepancies before their movements are completed (Rabbitt, 1978). Additionally, skilled typists were sometimes able to alter their behavioral response without accurate, conscious apprehension of their error (Logan & Crump, 2010).

Expert pianists performing in the absence of auditory and visual feedback did not differ statistically from pianists who were performing with only auditory feedback, in terms of the presence of a pre-ERN and its amplitude (Ruiz et al., 2009). It is likely that experts have built associations between the visual, tactile, and proprioceptive feedback they receive from their bodies and the resulting auditory feedback they receive from their instruments. This auditory-motor coupling allows the perception of erroneous keypresses without auditory feedback. In fact, the absence of auditory feedback seems to have no effect on the performance of well-learned piano pieces (Finney & Palmer, 2003; Pfordresher & Palmer, 2006).

The most recent investigations into the neurophysiological correlates of music performance have examined pianists playing scale-like patterns while researchers simultaneously gathered data from EEG recordings, MIDI keyboards, and three-dimensional movement sensors attached to pianists' fingers and hands (Maidhof, Kästner, & Makkonen, 2013); for review see Maidhof (2013). ERPs indicated a peak in increased negativity approximately 40 ms after tactile feedback was available to the pianist (as opposed to mid-air feedback as the finger was approaching the key) (Maidhof, 2013). Though auditory feedback may not be necessary for trained musicians, it is likely that when it is present, musicians still rely on the comparison between auditory and motor results (Finney & Palmer, 2003; Pfordresher & Palmer, 2006).

It is important to note, however, that deviations from this model have been recorded. Trained cellists changing pitches by shifting are more accurate when they performed the shift with auditory feedback than when they performed without it, suggesting that auditory feedback was an essential component in this domain (Chen et al., 2008). Perhaps more notably, string players shifting without their bow demonstrated less variability in their error-correcting finger movements (Chen et al., 2008), suggesting that for string players, an ongoing re-calibration process, dependent upon auditory feedback, was needed to produce accurate motor movements.

SUMMARY AND RESEARCH QUESTIONS

To encode and refine procedural memories learners must experience attempts to accomplish goals, perceive the discrepancies between the results of their attempts and their intended outcomes, and adjust their behavior to accommodate those discrepancies (Herzfeld & Shadmehr, 2014; Seidler et al., 2013; Wu et al., 2014). As learners make attempts at their goals and perceive the consequences of their movements, they create memories that can be activated when the same goal is attempted in the future (Herzfeld & Shadmehr, 2014; Wolpert & Ghahramani, 2000).

As musicians develop technique, they create procedural memories that pair their movements with the auditory and haptic outcomes of their movement. Moments of erroneous responses provide the feedback learners need to develop accurate associations that they can then exploit to achieve a specific auditory goal. When learners perceive discrepancies between what they are doing and what they intend to be doing, they learn.

Repetition of inaccurate movement does not hinder the motor system's ability to adapt and move effectively. The danger of inaccurate repetitions is that the perceptual system may no longer perceive repeated outcomes as inaccuracies—playing a C out of tune enough times can make an out-of-tune C sound in tune. Inaccurate repetitions do not so much hinder the motor system as they skew the perceptual system. Learners rely on the perceptual system to recognize errors, and skilled learners have a clear idea of what the intended sound will sound like, but also what it will look and feel like. Using this information during performance and practice may aid musicians in correcting or masking their errors in real-time.

It is true that practice is a time to eliminate errors, but effective music practice requires learners to set goals, make attempts toward those goals, and then perceive discrepancies between what they intend and what they do. Though all musicians work to eliminate errors from their performances, the development of music performance skills requires the refinement of both motor behavior *and perceptual skills* through an iterative process of goal setting, performance, and self-evaluation. This raises the question of how musicians' perceptions of errors change with increasing levels of skill development.

We hypothesize that as musicians develop expertise, they develop increasing levels of auditory and physical discrimination that then shift their intentions and expectations to increasing motor refinement and the formation of more precise and elaborate goals. In the research reported in this dissertation, we sought to determine whether the development of increasing skill and discrimination leads to a concomitant decrease in the frequency of error (as defined by the performer) during practice. Alternatively, perceived error rates during practice may remain relatively constant across the range of skill levels, perhaps as a result of increasing levels of discrimination and precision of musical intention.

This raises the question of how discrepancies are perceived by learners at different levels of experience and expertise. We designed three experiments to examine musicians' perceptions of their own practice and others' practice. In Experiment 1, immediately after recording their practice, high school, college, and professional musicians pressed a computer key to mark moments of discrepancy between what they intended while practicing and what they heard on their recordings; in Experiment 2, the high school and professional participants from Experiment 1 repeated the task 2 years later, listening to their original recordings; in Experiment 3, high school and professional participants heard practice recordings of four other violinists' practice (two artist-level experts and two competent students), and pressed the key each time they heard a discrepancy between what they heard on the recordings and what they would have intended had they been the practicer on the recording.

Chapter II: Experiment 1

In this experiment, we examined the extent to which musicians at different levels of experience identify discrepancies between their intentions and their actual playing during individual practice. Sixty musicians from four levels of skill development (high school, undergraduate music majors, graduate performance majors, and professional string players) practiced a familiar piece from their own repertoire for 5 minutes while being audio-recorded. Immediately following their practice, they listened to the recording and marked the points of discrepancy by pressing a computer key. There were no significant differences among the four levels of musical experience in either the mean rates of keypresses or the types of discrepancies participants identified, although within-group rates of keypresses presented with high variances. These results suggest that the development of music skills is not best characterized as a reduction in the rates of error during practice, and that the detection of discrepancies between intentions and outcomes is a central part of effective practice at all levels of experience and expertise.

METHOD

We recruited 60 musicians who played either violin, viola, cello, or bass; 15 were high school students who had played their primary instrument for at least three consecutive years (*M* years experience = 9.7 y; *M* age = 16.2 y; 10 female); 15 were undergraduate music majors (*M* years experience = 10.7 y; *M* age = 20.1 y, 9 female); 15 were graduate performance majors (*M* years experience = 16.7 y; *M* age = 25.8 y, 10 female); and 15 were professional musicians working in either an orchestra or university position (*M* years experience = 32.7 y; *M* age = 40.1 y, 7 female). The high school group comprised 4 violinists and 1 cellist; the undergraduate group comprised 6 violinists, 5 violists, 3 cellists, and 1 bassist; the graduate group comprised 5 violinists, 4 violists, 5 cellists, and 1 bassists; and the professional group comprised 9 violinists, 4 violists, and 2 cellists.

Participants were recruited by email from professional and educational music organizations within the community; all volunteered to participate in the study and received no compensation for their participation. The Institutional Review Board of The University of Texas at Austin approved all procedures. Consent and assent forms used for this study appear in Appendix A.

We tested participants in individual sessions that were scheduled at the convenience of the participants. We asked participants to bring with them to the test session an etude or piece that they were practicing at the time, one that was prepared beyond the note-reading stage, but was not yet performance-ready. When participants arrived for the testing session, we loosely followed the script presented in Appendix B. After a brief orientation to the testing room and a warm-up period, we recorded participants practicing their selected piece for approximately 5 min using a MacBook computer running QuickTime Player 10.4 (*QuickTime Player*, 2007).

Immediately following the 5-min practice period, participants listened through Bose Quiet Comfort 2 Acoustic Noise Cancelling headphones to the audio recording of their practicing, and as they listened, pressed a designated computer key each time they heard a discrepancy between *what they had intended* to do while practicing and *what had actually occurred*. We asked them to press the key for all discrepancies, regardless of whether they had noticed the discrepancies while they were practicing or only while they were listening to the recording.

We used SCRIBE 4 behavior analysis software (Duke & Stammen, 2011) to calculate the rate of keypresses per minute, which served as the primary dependent measure of the study. We calculated the rate of discrepancies for each participant by dividing the total number of keypresses by the total amount of time spent practicing (most sessions were a few seconds longer or shorter than 5 min).

Participants listened to their recordings only once, and following the listening we asked them to describe (1) whether they felt they had accurately marked the discrepancies they heard, (2) the extent to which the discrepancies they identified were heard during practice or only while listening to the recording, (3) to describe the nature of the discrepancies they identified, and (4) how long they had been working on the piece. These questions were presented informally in a way that allowed participants to respond freely about their experience; interview questions appear in Appendix C.

The primary author was present throughout the testing procedure for all participants and took written notes of participants' responses. After a preliminary review of the participants' responses about the nature of the discrepancies they identified, we grouped their responses into five categories: intonation (statements pertaining to precise finger or hand placement, playing in tune, or shifting in tune), tone (statements about quality of sound, bow control, or articulation), expression (statements about phrasing, inflection, vibrato, and dynamics), notes (statements about playing the correct notes, memorizing the correct notes, or creating playable fingerings), and timing (statements about tempo, fitting rhythms to a tempo, and coordinating left and right hands).

We determined which categories were represented by each participants' comments, referring to the primary author's written notes taken during the interviews. Most participants made comments in two or more categories. A trained reliability observer read *verbatim* transcripts of one third (n = 20) of the interviews and coded participants' responses using the same category system. Reliability between the primary author's codes and the observer's codes of the *verbatim* transcripts was 85% for intonation, 90% for tone, 95% for expression, 70%, for notes, and 95% for timing. Overall reliability was 87%.

The same reliability observer again coded participants' comments, this time from the primary author's written notes for all (*N* = 60) of the participants' statements. Reliability between the primary author's codes and the observer's codes was 98% for intonation, 98% for tone, 97% for expression, 82% for notes, and 95% for timing. Overall reliability was 94%.

Participants' answers regarding the length of time studying the pieces they practiced during the test session were placed into five categories: 1-7 days, 8-60 days, 61-120 days, 121-365 days, and a fifth category for participants who were relearning a piece that they had performed at sometime in the past. These categories were formulated after reviewing all participants' answers.

One important variable that may have affected the rates of perceived discrepancies among the four groups of participant is the suitability of the repertoire that each performer practiced for the study. We were curious as to whether the level of difficulty of each participant's piece was well matched to the technical capabilities of the participant practicing it. After listening to each 5-min practice recording, we rated the suitability of each participant's repertoire using a 5-point Likert-type scale, with 1 representing not well suited and 5 representing very well suited. An expert string teacher also independently listened to all 60 audio recordings and evaluated the repertoire's suitability using the same scale.

The level of agreement between the primary author's ratings of repertoire suitability and the expert observer's ratings was high. We both indicated that the repertoire played by all professionals, all graduate students, all undergraduate students, and 12 of the 15 high school students was well suited to their apparent level of technical proficiency (giving each recording a rating of either 4 or 5 on the scale described above). Of the three high school students whose pieces were thought to be less well suited to their technical proficiency, we both rated the suitability in the middle of the scale (giving a rating of 3 on the scale described above). We both agreed that there were no participants playing repertoire that was not well suited to their technical proficiency (there were no ratings of 1 or 2).

RESULTS

Accuracy of the Task

In order to confirm that participants believed that they had completed the task accurately, we asked at the end of the listening session whether the keypresses accurately reflected the number of discrepancies that participants had perceived while listening. Fifty-three of the 60 participants indicated that their keypresses accurately reflected the discrepancies they had heard. Nearly half the participants volunteered that their keypresses were slightly delayed (i.e., they pressed the key after a few moments had passed after detecting the discrepancy), which was not surprising given the nature of the task. The time required to initiate a keypress following a perceived discrepancy creates an inevitable lag.

Only 7 of the 60 participants indicated that there were small inaccuracies in their records of keypresses. Two of the participants (1 professional and 1 graduate student) reported they had missed a single keypress; four others (1 professional, 1 graduate student, 1 undergraduate student, and 1 high school student) reported that they missed "a few" keypresses due to the speed at which they were playing; and one professional participant reported losing concentration "for about 20-seconds" while listening. Given the small number of keypress errors that these participants described, we allowed all of the data to remain in the data set as recorded.

One professional participant was omitted from all keypress rate analysis due to a technical error while collecting data.

Mean Rates of Keypresses

We compared the rates of perceived discrepancies (rates of computer keypresses) among the four groups of participants in a one-way analysis of variance (ANOVA) and found no significant differences in mean keypress rates among the four experience levels, $F(3, 55) = 0.28$, $p = .84$. The overall group means were nearly identical among all four groups, although there were large variances within each group (High School $M = 4.62$, $SD = 2.97$, Undergraduate $M = 5.09$, $SD = 2.62$, Graduate $M = 5.03$, $SD = 3.95$, Professional $M = 5.67$, $SD = 2.76$). Figure 2.1 presents the individual data points for each participant in each experience category and the mean values for each experience level.

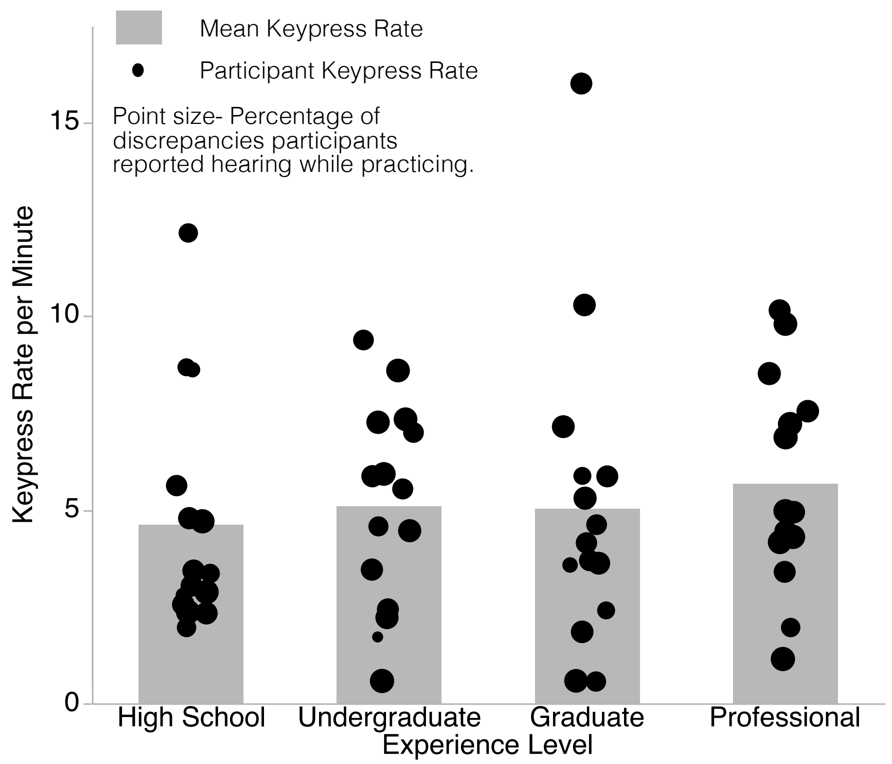


Figure 2.1. Keypress rate per minute by participant experience level. Bars represent group means. Point locations along the y-axis represent the keypress rates of individual participants; the size of each point indicates the percentage of discrepancies participants reported hearing while they were practicing. For example, the largest points represent participants who reported hearing all the discrepancies while they were practicing; the smallest point represents a participant who reported hearing only 15% of the discrepancies marked while practicing and the remaining 85% of discrepancies while listening to the recording.

Because experienced musicians often work on pieces they have already performed, we were interested in whether the participants in the present study were working on new repertoire or reviewing repertoire that had been learned and performed previously. Six of the professionals and 9 of the graduate students had selected repertoire for the study that they were learning for the first time. The remaining 9 professional participants and 6 graduate students had selected music that they had performed at some time in the past and were "relearning."

Since precisely half (n = 15) of the graduate students and professionals combined practiced new repertoire and half (n = 15) were relearning a familiar piece, we decided to compare the rates of discrepancies between these two serendipitous conditions. We examined just the data on rates of perceived discrepancies between two groups: graduate students and professionals who were working on a piece for the first time, and graduate students and professionals working on repertoire that they had previously performed. Using an independent-samples t-test, we found no difference in mean rates of keypresses between participants relearning a piece (M = 5.52, SD = 2.83) and participants who were learning a piece for the first time (M = 5.18, SD = 3.92), $t(27) = 0.27$, p = .79. Figure 2.2 presents the mean rates of keypresses for graduate and professional participants who were learning their pieces for the first time and graduate and professional participants who were relearning their pieces, along with the mean rates of keypresses for each category of repertoire familiarity.

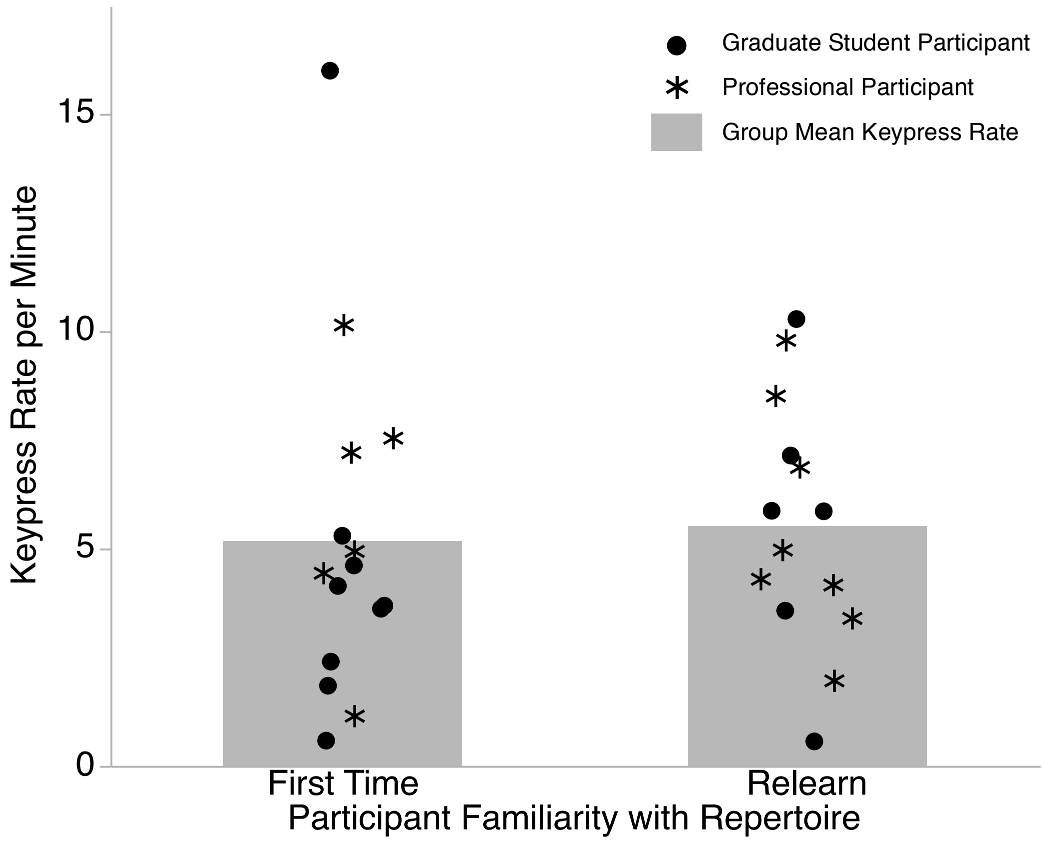


Figure 2.2. Keypress rates per minute of graduate and professional participants learning new repertoire and relearning familiar repertoire. Bars represent group means. Points represent the rates of keypresses for individual participants in each group. One professional participant was omitted from the analysis because of a technical error in collecting data.

We were also interested in whether the amount of time participants had practiced their pieces prior to the testing session would affect rates of perceived discrepancies. We grouped the participants using the following categories: 1-7 days preparation (n = 16), 8-60 days preparation (n = 15), 61-365 days preparation (n = 13), and relearning repertoire that was previously performed (n = 16). The distribution of preparation levels among the four levels of expertise is presented in Table 2.1. We compared the rates of perceived discrepancies in a one-way analysis of variance (ANOVA) and again found no significant difference in mean rates of keypresses among the four levels of preparation, $F(3, 55) = 0.39$, $p = .76$.

Table 2.1

Length of Preparation by Participant Experience Level

Level	Length of Preparation 1-7 Days	 8-60 Days	 61-365 Days	 Relearn
High School	2	4	8	1
Undergraduate	5	6	4	0
Graduate	4	4	1	6
Professional	5	1	0	9

Note. The number of participants at each stage of preparation (1-7 days, 8-60 days, 61-365 days, and relearning a piece) within each experience level (high school, undergraduate, graduate, and professional).

Participants estimated the percentage of discrepancies they heard while listening to the recording that they had *not* heard while practicing. The mean percentage across all participants was 21.1%. The professionals' mean estimate was much lower than the means for the other three groups (professionals, 10.3%; graduates, 25.9%; undergraduates, 20.3%; high school students, 27.3%), although this difference was not statistically significant, $F(3, 55) = 2.49$, $p = .07$. The size of the points in Figure 2.1 represent the percentage of discrepancies participants reported hearing while they were practicing. The largest points represent the participants who reported hearing all of the discrepancies they marked while they were practicing. The smallest point represents an undergraduate participant who reported hearing 15% of the discrepancies while practicing, and the other 85% while listening to the recording.

Types of Perceived Discrepancies

Participants described the types of discrepancies they heard on the recording. We coded each participant's comments according to the categories they mentioned; most participants made comments in two or more categories. We examined the distribution of discrepancy types among the four experience categories in a *chi*-square analysis. The numbers of discrepancies of each type in each experience category are presented in Table 2.2. We adjusted the number of categories in the statistical analysis to accommodate small numbers of observations in several cells. The resulting categories used in the *chi*-square test were intonation, tone, and other. We found no significant relationship between the experience level and the types of discrepancies participants described, $\chi^2(6, N = 122) = 0.91, p = .99$.

Table 2.2

Number of Participants Commenting About Types of Discrepancies by Experience Level

	Type of Perceived Discrepancies				
Level	Intonation	Tone	Notes	Expression	Timing
High School	13	8	2	3	3
Undergraduate	12	9	1	3	2
Graduate	12	10	3	3	3
Professional	13	12	6	2	2

Note. The number of student and professional participants who mentioned each type of discrepancy (intonation, tone, notes, expression, timing, practice) by excerpt. Most participants identified more than one type of discrepancy.
$\chi^2(6, 122) = 0.91$, $p = .99$ (with Notes, Expression, and Timing Columns combined due to small cell sizes)

Timing of Perceived Discrepancies

We examined individual participants' patterns of keypresses and found that, for all participants, keypresses were distributed throughout the practice sessions. One might have suspected that the number of perceived discrepancies would decrease over the course of a practice interval, but we did not find this to be the case.

We looked at the variability in the time intervals between keypresses by calculating each participant's coefficient of variation among the keypress intervals. Using a one-way analysis of variance (ANOVA), we found no significant difference among the coefficients of variation for high school participants (M = 69.53, SD = 11.20), undergraduate participants (M = 64.51, SD = 7.61), graduate participants (M = 68.55, SD = 6.58), and professional participants (M = 71.05, SD = 17.16), $F(3, 55) = 0.90$, $p = .45$.

Timelines of each participant's keypresses are displayed in Appendix D. Each row represents the sequence of keypresses by a single participant. Participants are grouped by experience level (high school, undergraduate, graduate, and professional) and, within each group, are arranged in order by number rate of keypresses. Some participants consistently pressed the key throughout their 5-minute practice session, whereas others had bursts of keypresses followed by moments devoid of any keypresses. The spacing of keypresses, however, did not vary systematically for learners at different levels.

DISCUSSION

Our results indicate that the number of discrepancies string musicians perceive in their own practice sessions does not vary systematically across levels of experience and expertise. We posit that as musicians learn over time, increasing levels of auditory and physical discrimination shift performers' intentions and expectations to increasing levels of refinement. Thus, experts' detection of discrepancies between intentions and outcomes may reflect clearer intentions, more vivid expectations, and finer levels of discrimination than are defined by less skillful players, though this conjecture must be subjected to further empirical scrutiny.

This is consistent with the current understanding of prediction error in learning (Diedrichsen, Hashambhoy, Rane, & Shadmehr, 2005; Diedrichsen, White, Newman, & Lally, 2010; Seidler et al., 2013). In order to execute and refine procedural memories, the central nervous system (CNS) receives information through sensory signals and sends motor commands to the musculoskeletal system (Wolpert & Ghahramani, 2000). When a learners' CNS generates a motor command, it also creates an efference copy, or an encoded representation of the expected sensory feedback. As musicians' movements unfold, the central nervous system receives proprioceptive, tactile, and auditory feedback that is then compared to the expected feedback stored in the efference copy. When there is a discrepancy between what happens and what the learner expects to happen, this prediction error signals the CNS to modify the movement parameters and more closely approximate the intended goal. To refine motor movement, then, learners must perceive feedback indicating the movement was incorrect. Thus, the effectiveness of practice is wholly dependent on the clarity and precision of learners' expectations.

Novice learners whose intention is merely to remember the c-natural, having played the c-natural, record no prediction error ("Nailed it!"), irrespective of whether the pitch was in tune or the tone was beautiful. Learners with more precise and elaborate expectations obtain more information with each repetition because the discrepancies between the vivid intention and the outcome are more starkly apparent. In the words of one professional participant in the current study, "you can make any note better."

Comments from a professional violinist and a high school violinist in the current study also illustrate this point. Both indicated that the discrepancies they identified were "always about intonation" and both demonstrated similar rates of keypresses while listening to their recordings. The high school student's intonation was generally worse than that of the professional, and he seldom made pitch adjustments after the onset of a mistuned note. The professional's intonation errors were not only smaller in magnitude than those of the high school student, but inaccuracies were corrected immediately following note onsets. Although both musicians perceived intonation discrepancies at similar rates, the quality of their intonation varied with respect to accuracy at note onset and speed of correction when errors occurred. The professional's intonation was clearly superior to the high school student's, but their perceptions of their own work were quite similar with respect to the number of intonation discrepancies they perceived.

It is perhaps unsurprising that both novice and expert string musicians addressed pitch accuracy during their practice; violinists, violists, cellists, and bassists must position each finger along the string with very little tolerance for positional errors lest they produce an inaccurate pitch. Further complicating the issue of intonation, though, is the issue of fingerings. Although composers and editors sometimes prescribe a set of fingerings for printed pitches, there is still a great deal of variability among string players in the fingerings they ultimately select for performance, sometimes requiring an elaborate process of trial and error during practice. One professional participant in the present study eloquently described the process as, "Figuring out the choreography of the piece," though many other professional musicians called it more simply, "Figuring out the notes."

String musicians consider individual differences in hand shape, technical abilities, and musical goals when deciding upon a set of fingerings for a given passage. Troublesome fingerings that do not fit an individual's hand shape or technical abilities are either practiced so that they become more consistent, or substituted with fingerings that better fit the performer. Fingerings that do not match a performer's hand shape or technical facility can become an undesired source of intonation variability, whereas better matched fingerings (or ill-fitting fingerings that have been practiced into consistency) are a source of artistic variability that provide an opportunity to make individualized espressive choices. With this in mind, it is unsurprising that both novice and expert string musicians perceived note and intonation discrepancies.

We found a great deal of variability within all four groups of participants (high school, undergraduate, graduate, and professional). The individual differences within groups are interesting and certainly warrant further study. It is notable that rates of keypresses were unrelated to how long participants had been working on their pieces, nor were they related to whether participants were relearning a piece that they had performed in the past.

The participants in the current study were asked to bring to the test session a piece they had been working on, and were told that they would be recorded while practicing. Fifty-seven of the 60 participants brought pieces at various stages of the learning process that were well suited to their skill level.

It seems reasonable that a performer working on more difficult repertoire relative to their skill level would have a greater opportunity for errors because the music poses additional challenges, and that this would result in the performer perceiving a greater number of discrepancies. It is interesting to note, however, that the three high school participants who brought repertoire that was less well suited to their current technical capabilities had self-perceived discrepancy rates of 3.4, 3.0, and 2.6 per minute and had worked on their piece for a week, a semester, and a year, respectively. All three participants' rates of keypresses were below the mean rate of keypresses for all participants (M = 5.1 keypresses per minute),

The primary dependent variable in the present study was not the number of errors in participants' practicing, but rather the rate at which participants perceived discrepancies between what they had intended and what they heard while practicing repertoire that was well suited to their technical capabilities. It is notable that among the most experienced performers in the sample (professional musicians and graduate students) the rates of perceived discrepancies did not differ between those who were learning a piece for the first time and those who were relearning a piece that they had performed at some time in the past. For this group of musicians, the mean rate of perceived discrepancies was not dependent on the familiarity of the repertoire.

A violinist in high school could produce a successful performance of a Mozart violin concerto and revisit the piece as a graduate student with more refined intentions. As a high school student he might use lovely inflection to shape the opening triad, but as a graduate student his technical and musical proficiency might include more refined bow changes and a continuous vibrato that would allow him to seamlessly connect the notes in the same opening triad. As a graduate student relearning this piece, he might come to perceive discrepancies between what he is doing and what he is now capable of doing during practice. These discrepancies would not be evidence of a learner who continues to produce errors in repertoire he has already learned, but a learner with more refined perceptions and more precise intentions.

With respect to practice sessions, the progression from novice to expert is not characterized primarily by a diminution in the rate of error making, but rather by an apparent *increase* in the elaboration and refinement of intentions and expectations. Common aphorisms like *Perfect practice makes perfect* imply that flawless performance requires practice time filled with flawless repetitions. Although it is true that musicians at all levels work to eliminate errors, data from the present study suggest that as musicians develop increasing levels of auditory discrimination, they perceive finer discrepancies between what they intend and what they do. These revised expectations guide practice behavior and lead to increasing levels of motor refinement over time.

Chapter III: Experiment 2

The design of Experiment 1 allowed us to examine musicians' perceptions of their own work, making comparisons between high school students, undergraduates, graduate students, and professionals. We were also interested in whether individual participants' perceptions of their own work would change with the passage of time, leading to the design of Experiment 2.

Approximately two years after the completion of Experiment 1, we recruited 24 of the Experiment 1 participants and asked them to repeat the task of identifying discrepancies between their intentions and their actual playing in the 2-year-old recordings. In Experiment 1, these student and professional string players practiced a familiar piece from their own repertoire for 5-minutes while being audio-recorded, after which they listened to the recording and, by pressing a designated computer key, marked instances of discrepancy between what they had intended and what they actually played as they practiced. In Experiment 2, participants again listened to their 2-year-old recording and again indicated points of discrepancy between their intentions and outcomes. Professional participants marked discrepancies at approximately the same rates as they had done immediately after making the recording. Student participants, however, indicated significantly more discrepancies in the current study than they had immediately after making the recording. These results suggest that as musicians learn over time, increasing levels of auditory and physical discrimination shift performers' intentions and expectations to increasing levels of refinement.

Method

We contacted the 15 high school musicians and the 15 professional musicians who had participated in Experiment 1 approximately 2 years after their first testing session (*M* test interval = 1.8 y, 1.5 y – 2.3 y). Thirteen of the original 15 student participants (*M* years experience = 11.2 y; *M* age = 17.8 y; 9 female), and 11 of the original 15 professional musicians (*M* years experience = 35.0 y, *M* age = 41.2 y, 6 female) agreed to participate in Experiment 2.

Five of the student participants were in high school at the time of Experiment 1 and were still in high school at the time of Experiment 2. The remaining student participants were in high school at the time of Experiment 1 and had begun college classes at the time of Experiment 2 (five as music majors, one as an undeclared major with the intent of becoming a music major, and two as non-music majors). All professional musicians from Experiment 1 were still performing professionally at the time of Experiment 2.

All participants volunteered to participate in the study and received no compensation for their participation. The Institutional Review Board of The University of Texas at Austin approved all procedures. Consent and assent forms used for this study appear in Appendix E.

We tested participants in individual sessions that were scheduled at their convenience. Participants listened to audio recordings of their own 5-min practice sessions that had been recorded 2 years earlier (during Experiment 1), and, as before, pressed a designated computer key to mark each time they heard a discrepancy between their *current* musical intentions and what they heard on the recording. We explained the task in pre-recorded video instructions using the script presented in Appendix F.

Participants listened to the instructions and the excerpts through Bose Quiet Comfort 2 Acoustic Noise Cancelling headphones attached to a MacBook laptop computer.

We used SCRIBE 4 behavior analysis software (Duke & Stammen, 2011) to link the participants' keypresses to their recordings and to calculate the rate of keypresses per minute, which served as the primary dependent measure of the study. We calculated the rate of discrepancies for each participant by dividing the total number of keypresses by the total practice time on the recording (most sessions were a few seconds longer or shorter than 5 min).

Participants listened to each recording only once, after which we asked them to describe (1) whether they felt they had accurately marked the discrepancies they heard, (2) the nature of the discrepancies they identified, and (3) whether they had any additional observations or comments about the experience. These questions were posed informally in a way that allowed participants to respond freely about their experience; interview questions appear in Appendix G.

The primary author was present throughout the testing procedure for all participants and took written notes of participants' responses. We coded participants' responses about the nature of the discrepancies they perceived using the following definitions: intonation (statements pertaining to precise finger or hand placement, playing in tune, or shifting in tune), tone (statements about quality of sound, bow control, or articulation), expression (statements about phrasing, inflection, vibrato, and dynamics), notes (statements about playing the correct notes, memorizing the correct notes, or creating playable fingerings), timing (statements about tempo, fitting rhythms to a tempo, and coordinating left and right hands), and practice (statements about the quality or type of practice).

Five of the six categories (intonation, tone, expression, notes, and timing) were established in Experiment 1 after examining participants' open-ended responses about the nature of discrepancies they perceived in their practice. In the current study, many participants, in addition to identifying aspects of playing that led to their keypresses, offered comments about how they were practicing during the recordings, thus we added the sixth category (practice) to our coding system.

We determined which categories were represented by each participants' comments, referring back to the primary author's written notes taken during the interviews. Most participants made comments in two or more categories. A trained reliability observer read *verbatim* transcripts of 20% of the interviews (n = 8) and coded participants' responses. Reliability between the primary author's notes and the observer's codes of the *verbatim* transcripts was 100% for intonation, 63% for tone, 100% for expression, 88% for notes, 88% for timing, and 88% for practice. Overall reliability was 88%.

The same reliability observer again coded participants' comments, this time from the primary author's written notes for all (N = 24) of the participants' statements. Reliability between the primary author's codes and the observer's codes was 96% for intonation, 88% for tone, 96% for expression, 96% for notes, 92% for timing, and 96% for practice. Overall reliability was 94%.

RESULTS

Accuracy of the Task

We asked participants at the end of the listening session whether the keypresses accurately reflected the number of discrepancies that they had perceived while listening.

All 24 participants indicated that their keypresses accurately reflected the discrepancies they had heard.

Similar to Experiment 1, five of the 24 participants volunteered that keypresses were slightly delayed (i.e., they pressed the key after a few moments had passed since detecting the discrepancy). This was not surprising given the nature of the task. The time required to initiate a keypress following a perceived discrepancy creates an inevitable lag.

Two of the 24 participants indicated that there were small inaccuracies in their records of keypresses. One participant said she had accidentally pressed the key once without perceiving a discrepancy, and the other said she may have missed a few keypresses. Given the small numbers of keypress errors that these participants described, we allowed all of the data to remain in the data set as recorded.

Mean Rates of Keypresses

We compared participants' keypress rates from Experiment 1, just after they had recorded their practice, to their rates in the current experiment and calculated a difference score for each participant. Figure 3.1 shows each participant's keypress rate in Experiments 1 and 2. All but one student, an outlier marked with an asterisk, heard discrepancies less frequently at the time they made the recording than they did two years later. Most professional musicians heard discrepancies at about the same rate regardless of whether they were listening to the recording at the time they made it or two years later. Two professional participants, both outliers marked with asterisks, heard discrepancies much more frequently two years after they made the recording than they did at the time of recording.

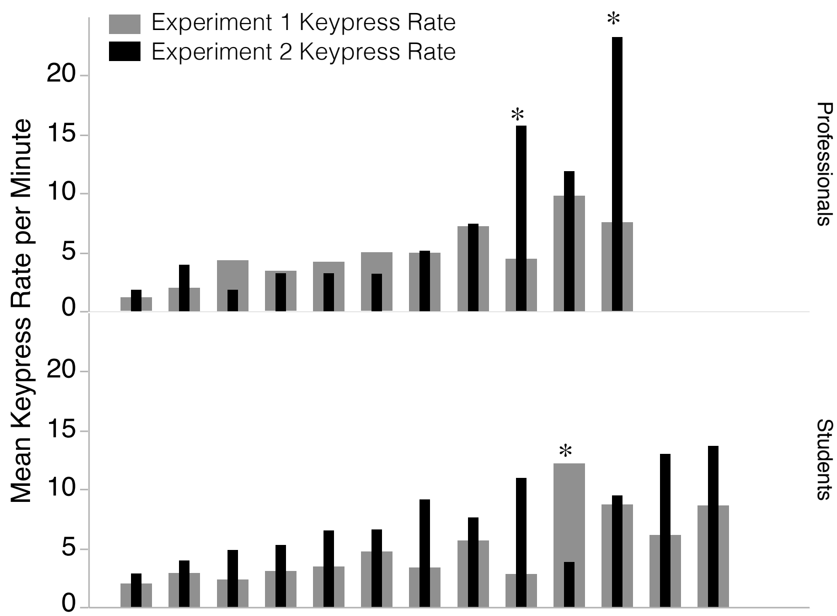


Figure 3.1. Mean keypress rate per minute collected during Experiment 1 and Experiment 2. Grey bars represent participants' rates of keypresses collected during Experiment 1 and black bars represent participants' rates of keypresses collected 2-years later during Experiment 2. Participants in each group (students, professionals) placed in order of increasing mean keypress rates from left to right. Outliers indicated with asterisks.

We calculated individual keypress rate difference scores between Experiments 1 and 2 and found three outliers among the participants (whose difference scores fell 1.5 times the interquartile range above the third quartile or below the first quartile), one student participant with a difference score of -8.35 keypresses per minute, and two professional participants with difference scores of 11.28 and 15.69 keypresses per minute. Figure 3.2 presents the difference scores for individual participants within each group (students and participants); outliers are marked with asterisks. We excluded these participants' data from all subsequent analyses and graphs.

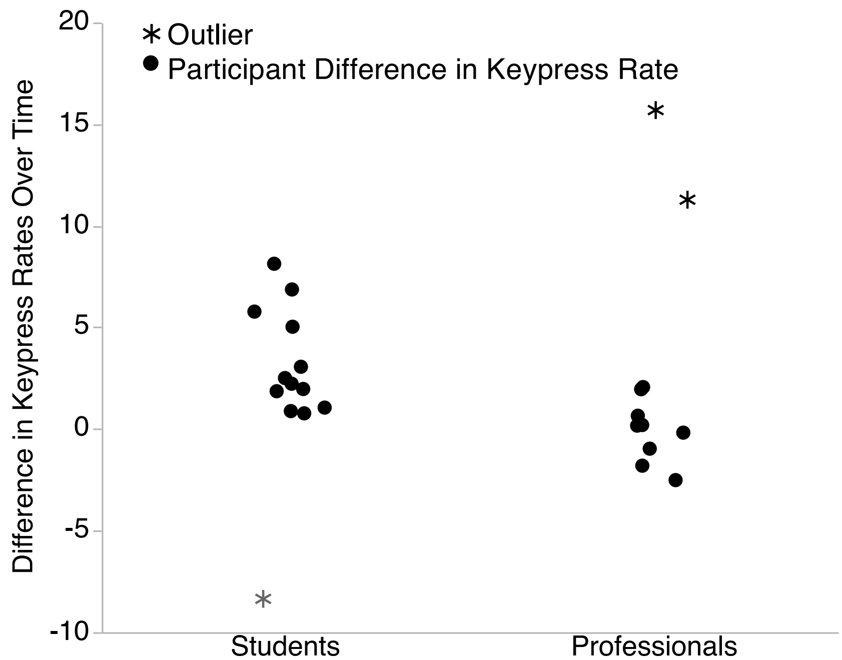


Figure 3.2. Difference in participants' rate of keypresses collected during Experiment 1 and Experiment 2. Difference between mean keypress rates in Experiment 1 and Experiment 2 for student and professional participants. Points represent individual participants' mean rates of keypresses while listening to their own practice recordings, asterisks represent outliers.

Using an independent-samples *t*-test, we found a significant difference between the mean difference scores of professional participants (M = -0.05, SD = 1.55) and student participants (M = 3.35, SD = 2.49); student participants' mean rates of keypresses increased significantly more than professional participants' over the 2-year interval between Experiments 1 and 2, $t(19) = 3.59$, $p < .001$.

We compared the mean rates of keypresses by student and professional participants taken from Experiment 1 and 2 using a two factor analysis of variance with repeated measures. We found no significant difference between the mean rates of keypresses by students and professionals overall, $F(1,19) = 1.53$, $p = .23$. We found a significant difference between the mean rates of keypresses attributable to time points, $F(1,19) = 12.19$, $p = .002$, and a significant interaction between group and time point, $F(1,19) = 12.89$, $p = .002$. Professionals identified discrepancies at highly similar rates during Experiments 1 and 2 ($M_{EXP1} = 4.65$, $SD_{EXP1} = 2.62$; $M_{EXP2} = 4.61$, $SD_{EXP2} = 3.22$), but students identified significantly more discrepancies during Experiment 2 than they had during Experiment 1 ($M_{EXP1} = 4.46$, $SD_{EXP1} = 2.33$; $M_{EXP2} = 7.80$, $SD_{EXP2} = 3.48$). In both experiments, within group variances were high. Figure 3.3 shows the mean keypress rates from Experiments 1 and 2 for student and professional participants.

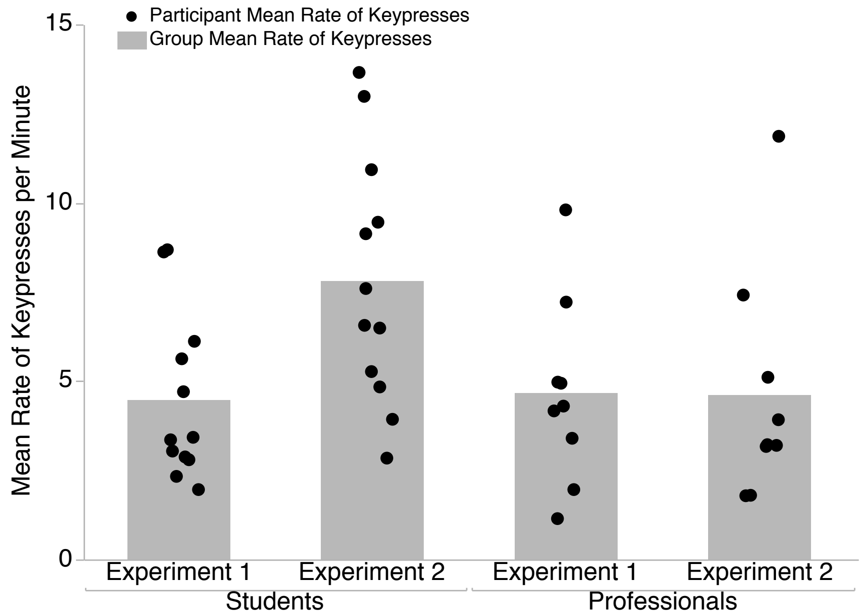


Figure 3.3. Participants' rates of keypresses in Experiment 1 and 2 by experience level. *Note*. Student and professional participants' mean rate of keypresses collected during Experiment 1 and 2. Grey bars represent group means. Points represent participants mean keypresses rate per minute. Three outliers were removed from data set.

Types of Perceived Discrepancies

After completing the keypress task, participants gave their impression about the types of discrepancies they heard on the recording. We coded each participant's comments according to the categories they mentioned; most participants made comments in two or more categories. The numbers of discrepancies of each type in each experience category are presented in Table 3.1. As with Experiment 1, student and professional participants heard similar types of discrepancies.

Table 3.1

Number of Student and Professional Participants Commenting About Types of Discrepancies

Time	Type of Perceived Discrepancies					
	Intonation	Tone	Notes	Expression	Timing	Practice
			Students, *n* = 13			
Exp 1	13	8	2	3	3	-
Exp 2	12	11	0	7	1	5
			Professionals, *n = 11*			
Exp 1	13	8	2	3	3	-
Exp 2	10	5	3	4	2	4

Note. The number of student and professional participants who mentioned each type of discrepancy (intonation, tone, notes, expression, timing, practice) by time point. Most participants identified more than one type of discrepancy.

We compared each participant's responses about the types of discrepancies they perceived during Experiment 2 to the types of discrepancies they perceived 2-years earlier during Experiment 1, making a comparison only between the 5 categories we included in Experiment 1 (intonation, tone, expression, notes, and timing). For each participant, we calculated the percentage of agreement between the types of discrepancies they mentioned immediately after making the recording (during Experiment 1) and the types of discrepancies they mentioned two years later (during Experiment 2). We found no significant difference in the rates of agreement between student (M = 0.72, SD = .15) and professional participants (M = 0.71, SD = .23), $t(22)$ = 0.18, p = .86.

Timing of Perceived Discrepancies

We examined individual participants' patterns of keypresses and compared these to the patterns of keypresses recorded in Experiment 1, two years prior. We found that for all participants, keypresses were distributed throughout the practice sessions and results from Experiment 1 and 2 were very similar.

Timelines of each participant's keypresses are displayed in Appendix H. Each set of rows represents the sequence of keypresses by a single participant. The top row of each set represents the participant's keypresses recorded during Experiment 1, and the bottom row represents the keypresses recorded in Experiment 2. Participants are grouped by experience level (student, professional) and, within each group, are arranged in order by mean rate of keypresses.

DISCUSSION

Our results indicate that as young musicians develop skills and mature over time, they identify more discrepancies in their own playing during a recorded practice session. Professionals, however, evince no such change in their perceptions of discrepancies between their musical intentions and what they hear in their own playing. Student musicians who heard a 2-year-old recording of their own practicing indicated discrepancies between their current intentions and their recorded performances significantly more frequently than they had immediately after the recording was made.

These data are consistent with the notion that the development of musical expertise involves not only increasing levels of physical skill but also commensurately increasing levels of intentional precision and refinement of auditory discrimination. This interpretation is in keeping with our current understanding of motor learning: that as learners attempt to accomplish tangible goals, the sensory feedback they receive about the effects of their movements serves to modify motor commands both as movements unfold and during future attempts to accomplish similar goals. This raises an important issue about musical development, namely, that a major inhibitor of learners' progress is a lack of refinement in goal setting. The motor system can obtain only as much information from a given movement as the movement's goal is clear in the mind of the learner. The clearer the goal, the greater the opportunity for information from each iteration of the movement.

We interviewed participants after they completed the listening task by asking them about the experience of listening to a 2-year-old recording of their practice session. One developing musician pressed the computer key 2.3 times per minute (13 keypresses) when he listened to his practice recording as a freshman in high school and then pressed it 4.8 times per minute (27 keypresses) when he completed the task 2 years later as a junior. He stated, "It's kind of cool [to do this task] because I just played that [repertoire] the other day… I can tell that I've improved a lot, actually. So, it's really cool to see that."

This stands in contrast to some of the professional participants who suggested they were pleasantly surprised by their recording. One highly skilled expert pressed the computer key 4.2 times per minute (22 keypresses) during Experiment 1 and 3.2 times per minute (17 keypresses) during Experiment 2. She commented, "I was dreading this… but the good thing was I was pleasantly surprised. I liked my vibrato. I think hearing it back a couple of years later, it was nice to be like, OK, that's better than I thought [it was going to be]."

Another highly experienced participant commented, "Well I was pleasantly surprised… I think we're so critical and there are still so many moments when I was…," as she pressed the computer key in rapid succession with a look of frustration on her face. She continued, "But overall, I was like, 'Oh, that's me. That sounds good!'" It is especially interesting to note that this participant felt a sense of accomplishment despite feeling as if she pressed the computer key very frequently. Her definition of skilled playing was not simply a function of the number of discrepancies she perceived in her practice.

It seems reasonable that she could have been listening to the magnitude and hierarchy of the errors she perceived and that this would then inform her perception of her playing. For example, a skilled listener who can perceive notes that are greatly out of tune and notes that are just a little out of tune would press the computer key the same way in both instances. This same listener might, however, take the magnitude of the intonation discrepancies into consideration when assessing her overall playing, recognizing that greatly out of tune notes are errors of a different magnitude than slightly out of tune notes that are quickly corrected.

The design of this experiment allows us to make a direct comparison between student and professional participants' rates of keypresses at two different points in time. We made no attempt to influence what participants learned between experiments, of course, and we did not measure changes that may have taken place in participants' performance skills over the two-year interval.

The data from this experiment are consistent with the hypothesis that refinement of physical skills occurs in concert with refinement of performance goals and with increasingly acute auditory perceptions. In Experiment 1, both student and professional participants marked discrepancies immediately after recording their practice, when their levels of discernment matched their levels of performance capabilities. Between Experiments 1 and 2, student participants' levels of discernment had changed, as evidenced by their marking more points of discrepancy as they listened to recordings they had made two years earlier. In contrast, professional participants had reached a level of artistic mastery at the time of Experiment 1, and their levels of discernment and their performance capabilities were likely quite similar during both experiments.

These results contribute not only to the formulation of a model of expertise in music, but also to pedagogical practice. It is often the case that music teachers focus in individual lessons on giving clear instructions and pointed feedback intended to modify various aspects of students' playing. Less often are learners directed to think carefully and explain clearly their intentions about what they set out to accomplish in each performance trial.

Chapter IV: Experiment 3

The design of Experiments 1 and 2 allowed us to make comparisons between what student and professional musicians perceived in their own practice sessions, while they were practicing a piece they selected to practice during Experiment 1. We were also interested in examining the extent to which musicians at different levels of experience and expertise identify discrepancies between their own expectations for music performance and what they hear in recordings of *other* musicians' playing. In Experiment 3, 54 student and professional string musicians listened to recordings of four anonymous violinists practicing: two competent high school violinists and two professional violinists. We asked participants to imagine as they listened that they were the musician practicing in each recording and to press a computer key each time they heard a discrepancy between the performance on the recording and what they *would have intended* if they had been the musician on the recording.

We found that professional musicians perceived significantly more discrepancies than did student musicians in all four recordings, and there were large within-group variances. Interestingly, the mean number of discrepancies identified by each group of listeners did not differ among the four recordings; that is, both student and professional musicians marked similar numbers of discrepancies, regardless of whether they were listening to a recording of a competent high school student or a professional musician. These results lend further support to the proposition that auditory perception and refined intentionality are central aspects of musical expertise, and that one of the characteristics that differentiates competent performers from experts is the extent to which experts perceive discrepencies between clear musical goals and outcomes.

METHOD

Participants

We recruited 54 musicians who played violin, viola, cello, or bass. Twenty-eight participants were student musicians who had played their instrument for at least 3 years (*M* years experience = 9.4 y; *M* age = 16.8 y, 16 female). Thirteen student participants had participated in Experiments 1 and 2. Five of these 13 returning student participants were in high school when they participated in Experiment 1 and were still in high school when they completed Experiment 3; the remaining eight returning student participants were in high school when they participated in Experiment 1 and had begun college when they participated in Experiment 3 (five as music majors, one as an undeclared major with the intent of becoming a music major, and two as non-music majors). The 15 student participants who had not participated in any previous experiments were all in high school at the time of testing.

In addition to the 28 student participants, we recruited 26 highly skilled professionals (*M* years experience = 33.6 y; *M* age = 41.7 y, 15 female). These musicians either held a faculty position within a school of music at a university or performed in a regional symphony. Eleven of these participants had also participated in both Experiments 1 and 2.

New and returning participants were recruited by email from professional and educational music organizations within the community; all volunteered to participate in the study and received no compensation for their participation. The Institutional Review Board of The University of Texas at Austin approved all procedures. We present the consent form completed by adult participants in Appendix E.

We tested participants in individual sessions that were scheduled at the convenience of the participants. Participants who participated in Experiment 2 and the current study completed these both in a single test session with a brief break between the two studies, during which participants listened to instructions and practiced the second task.

Auditory Stimuli

Participants listened to 2-minute excerpts of four anonymous violinists practicing, hereafter referred to as *Student 1*, *Student 2*, *Expert 1*, and *Expert 2*. All four of these violinists had recorded their practice sessions while participating in Experiment 1, and all consented to having their recording used as auditory stimuli in Experiment 3. At the time the recording was made, Student 1 and Student 2 were both competent high-school-aged musicians with demonstrated success in their respective schools' orchestra programs and in their respective private teachers' studios. Expert 1 and Expert 2 are highly regarded violinists with distinguished performing and recording careers, in addition to being highly regarded violin teachers.

We considered several criteria when selecting the 2-min excerpts used as auditory stimuli. First, we used only violinists for all four auditory stimuli to allow for a comparison in the mean rate of keypresses between string musicians listening to someone playing their own instrument (violinists) and string musicians (violists, cellists, bassists) listening to someone playing a different instrument. Second, we used only successfully completed rehearsal frames, moments in which the violinist made an attempt or a series of attempts toward a tangible musical goal and subsequently accomplished that goal (Duke, 1994). The final attempt in all four recordings was a successful, audible accomplishment of something each performer had been working on during the 2-min excerpt.

In terms of the keypress rate, these excerpts were fairly representative of each participant's entire 5-min recording, although, according to their own assessments, the students' excerpts represented some of their better work and the experts' excerpts represented some of their more error-prone work. In other words, we selected moments when the students were successful and moments when the expert violinists were actually working to accomplish a goal; all examples feature a performer working on a tangible goal that was ultimately solved by the end of the excerpt.

Figure 4.1 depicts a timeline of each performer's keypresses while listening to their entire practice session as recorded in Experiment 1. The area highlighted grey represents the excerpt used as auditory stimuli for the present experiment.

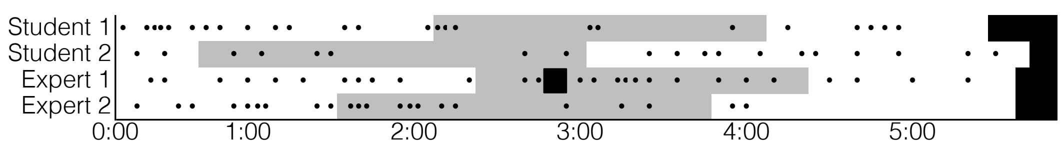


Figure 4.1. Timeline of performers' keypresses while listening to their own practice. Each point (•) represents a keypress (an indication that the performer perceived a discrepancy between what they had intended and what they had heard) during a 5-min long practice session recorded and evaluated in Experiment 1. Grey denotes the excerpt used as auditory stimuli for the present experiment. The black section in the recording of Expert 1 denotes 9-sec clip that was spliced out to maintain the performer's anonymity.

Student 1

At the time of the recording, Student 1 was in her last year of high school and was about to attend a state university with a scholarship as a violin performance major. Prior to the testing session, she had played violin for 13 years and had taken private violin lessons throughout the duration of her studies. She regularly held leadership positions within her school orchestra and youth symphony and had attended music festivals during the summers. She selected for her practice session the second movement (Adagio) of *Violin Concerto No. 1, Op. 26* by Max Bruch (Bruch, 1951), a piece rooted in traditional Western tonality and commonly studied in traditional pedagogical sequences. At the time of the test session, Student 1 had been working on this piece for 6 weeks.

During Experiment 1, she practiced for a total of 5 min, 19 sec, and we extracted an excerpt that was 1-min 55-sec long to use as an auditory stimulus in the present experiment. During this excerpt, Student 1 is initially practicing a shift from first position to 4^{th} position. After several successful repetitions, she practices approaching the shift within the larger context of the passage, lyrical, arpeggiated chords that present both intonation and string-crossing challenges. When listening to the recording of her practicing in Experiment 1, Student 1 indicated 5 discrepancies between what she had intended and what she heard in this excerpt (2.61 discrepancies per minute). When asked to describe the types of discrepancies that lead her to press the computer key, she mentioned only intonation.

Student 2

Student 2 was a high school junior who consistently participated in school orchestra and began his studies during sixth grade. At the time of the recording, he had played violin for 5.5 years and had been taking lessons since he entered high school. He brought to the practice session the first movement (Allegro non troppo) of *Symphonie*

Espagnole, Op. 21 by Édouard Lalo (Lalo, 1908), a piece rooted in traditional Western tonality and commonly studied in traditional pedagogical sequences. At the time of the testing session, Student 1 had been working on the piece for 1 month.

During Experiment 1, he practiced for a total of 5 min, 33 sec, and we extracted an excerpt that was 2-min 10-sec long to use as an auditory stimulus for the present experiment. During this excerpt, Student 2 worked on the shifting patterns within a fast (16^{th} note) ascending arpeggiated passage. Throughout his time practicing he uses a metronome, initially setting it to 8^{th} note equals 82 beats per minute (bpm) and later increasing it to 92, 100, and 110 bpm. At one moment he maintains the tempo coming from the metronome, but plays the passage at half tempo (with the beat equaling the 16^{th} note, rather than the 8^{th} note). He finishes the excerpt by again maintaining the tempo coming from the metronome, but plays the passage in double tempo (with the beat equaling the quarter note). When listening to recording of his practicing in Experiment 1, Student 2 indicated 6 discrepancies between what he had intended and what he heard in this excerpt (2.75 discrepancies per minute). When asked to describe the types of discrepancies that lead him to press the computer key, he said they were always related to intonation.

Expert 1

Expert 1 is a professional violinist who is frequently engaged as a soloist and chamber musician in live and recorded performances. At the time of the recording, she had played violin for 36 years. She brought to the practice session the first movement (Allegretto ben moderato) of *Sonata for Piano and Violin in A Major* by César Franck (Franck, 2016), a frequently performed piece rooted in Western tonality. She reported that she had performed the piece approximately 20 years earlier, and that she was reviewing it for an upcoming recital. She had begun to rework the piece just once prior to the test session.

During Experiment 1, she practiced for a total of 5 min, 17 sec, and we extracted an excerpt that was 2-min and 9-sec long to use as the auditory stimuli for the present experiment. To preserve her anonymity, we spliced out a 9-sec segment during which she hummed the passage she was practicing. This made the total duration of the clip exactly 2 min. During this excerpt, Expert 1 is establishing a fingering (determining which fingers to use for which notes) during an expressive, lyrical passage. She experiments with three different sets of fingerings and two different patterns of inflection, often stopping herself midway through repetitions. When listening to recording of her practicing in Experiment 1, she indicated 11 discrepancies between what she had intended and what she heard in this excerpt (5.50 discrepancies per minute). When asked to describe the types of discrepancies that led her to press the computer key, she said intonation as well as tone at the ends of notes, before string crossings, and before shifts.

Expert 2

Expert 2 is also a professional violinist who is frequently engaged as a soloist and chamber musician in live and recorded performances. At the time of the recording, he had played violin for 38 years. He brought to the test session the second movement (Scherzo: Allegro) of *Violin Concerto No. 1, Op. 77* by Dmitri Shostakovich (Shostakovich, 1957), a lesser-known piece that departs somewhat from common-practice tertian harmony. The scherzo movement is characterized by uneven patterns of inflection set against a steady rhythmic pulse. Expert 2 had just begun playing the piece for the first time 15 minutes prior to the test session.

During Experiment 1, he practiced for a total of 5 min, 28 sec, and we extracted an excerpt that was 1-min 58-sec long to use as an auditory stimulus for the present experiment. During this excerpt he is practicing an arpeggiated lyrical pattern that presents challenges because the intervals between notes lie outside a typical hand frame pattern. He experiments with several different fingering patterns, often stopping himself midway through repetitions. When listening to a recording of his practicing in Experiment 1, he indicated 12 discrepancies between what he had intended and what he heard in this excerpt (6.10 discrepancies per minute). When asked to describe the types of those discrepancies that lead him to press the computer key, he said intonation and figuring out the notes.

Procedure

As participants listened to the excerpts, they were asked to press a designated computer key each time they heard a discrepancy between what they heard and what they would have intended if this were a recording of their own practicing. We explained the task in pre-recorded video instructions using the script presented in Appendix I. Participants listened to the instructions and the excerpts through Bose Quiet Comfort 2 Acoustic Noise Cancelling headphones attached to a MacBook laptop computer. Due to a technical error, 2 participants listened to the recordings through internal stereo speakers of the Apple laptop computer. The data from these two participants fell with in the interquartile range of all participants, indicating that listening through speakers rather than headphones had not appreciably affected their responses, and we decided to include their data in the analyses below.

After listening to the recorded instructions, we asked participants to practice the keypress task by listening to a 24-sec audio excerpt of a violinist practicing. There were very salient intonation errors in the recording. We asked participants to imagine as they listened that they were the musician practicing in the recording and to press a computer key each time they heard a discrepancy.

Immediately following the practice example, participants were provided an opportunity to ask the proctor questions. Participants were again reminded to press the computer key to mark all discrepancies between the performance on the recording and what they *would have intended* if they had been the musician on the recording Participants then listened to all four test recordings. After each recording, the proctor asked participants a series of questions that we describe below.

The four excerpts were presented to participants in one of four possible orders (see Table 4.1); we randomly assigned orders to participants with the restriction that there be an equal number of presentation orders in each group of participants (new students, returning students, new professionals, and returning professionals).

Table 4.1

Order of Excerpts within Each Auditory Excerpt Pattern

	Order of Excerpts			
Pattern	1st	2nd	3rd	4th
1	Student 1	Student 2	Expert 1	Expert 2
2	Expert 2	Expert 1	Student 2	Student 1
3	Expert 1	Student 1	Expert 2	Student 2
4	Student 2	Expert 2	Student 1	Expert 1

Note. Patterns randomly assigned to participants with restrictions (equal distribution across groups).

Before starting the task, participants were informed, “You may not know the pieces these individuals are working on and they may be playing an instrument that is different from your own.” Participants listened to the auditory examples without looking at a score. We did not ask them to identify discrepancies between a written score and what they heard on the recording, but instead to identify discrepancies between the performance on the recording and what they *would have intended* if they had been the musician on the recording. We instructed participants to press a designated key on the computer “every time you hear something that deviates from what you would want if this were a recording of you practicing right now. For example, you may hear a phrase ending where the last note doesn’t end beautifully or a passage during which the style of articulation is inconsistent or notes that are out of tune.”

As participants were listening and pressing the key, we used SCRIBE 4 behavior analysis software (Duke & Stammen, 2011) to link the participants’ keypresses to the recordings and to calculate the rate of keypresses per minute, which served as the primary dependent measure of the study. We calculated the rate of discrepancies for each participant by dividing the total number of keypresses by the total playing time of each recording.

Participants listened to each recording only once, and then were asked to describe (1) whether they felt they had accurately marked the discrepancies they heard, (2) the nature of the discrepancies they identified, (3) how familiar they were with the repertoire on the recording, (4) how well suited the piece was to the performer’s skill level, (5) whether it was appropriate for a string teacher to assign the piece to the performer on the recording, and (6) the performer’s experience level. These questions were posed informally and allowed participants to respond freely; interview questions appear in Appendix J.

The primary author of the study served as the test proctor and took written notes of participants' responses during the brief question period. We coded participants' responses about the nature of the errors they perceived using the following definitions: intonation (statements pertaining to precise finger or hand placement, playing in tune, or shifting in tune), tone (statements about quality of sound, bow control, or articulation), expression (statements about phrasing, inflection, vibrato, and dynamics), notes (statements about playing the correct notes, memorizing the correct notes, or creating playable fingerings), timing (statements about tempo, fitting rhythms to a tempo, and coordinating left and right hands), and practice (statements about the quality or type of practice).

Five of the six categories (intonation, tone, expression, notes, and timing) were established in Experiment 1 after examining participants' open-ended responses about the nature of discrepancies they perceived in their own practice. In the current study, we again asked participants to describe the types of discrepancies they perceived. A number of participants made observations about the practice procedures they heard on the recordings so we added the sixth category (practice) to our coding system.

We determined which categories were represented by each participants' comments, referring back to the primary author's written notes taken during the interviews. Most participants made comments in two or more categories. A trained reliability observer read *verbatim* transcripts of 20% of the interviews (n = 44) and coded participants' responses. Reliability between the primary author's notes and the observer's codes of the *verbatim* transcripts was 89% for intonation, 93% for tone, 95% for expression, 89%, for notes, 95% for timing, and 91% for practice. Overall reliability was 92%.

The same reliability observer again coded participants' comments, this time from the primary author's written notes for all (N = 216) of the participants' statements. Reliability between the primary author's codes and the observer's codes was 94% for intonation, 91% for tone, 92% for expression, 91% for notes, 92% for timing, and 91% for practice. Overall reliability was 92%.

Participants responded about their own familiarity with the repertoire on the recording using a 5-point Likert-type scale, with 1 representing "never heard the repertoire" and 5 representing "performed the repertoire in public." Participants also reported on how well suited the repertoire was to the performer's skill level using a 5-point Likert-type scale, with 1 representing "not well suited" and 5 representing "very well suited." Finally, participants estimated each performer's experience level by selecting one of the following four categories: high school, undergraduate music major, graduate performance major, and professional musician with a position with an orchestra or university.

RESULTS

Accuracy of Task

In order to confirm that participants believed they had completed the task accurately, we asked each participant whether they felt their keypresses accurately reflected the discrepancies they perceived immediately after they listened to each recording. Fifty-two of the 54 participants indicated that their keypresses were an accurate reflection of what they had perceived.

Two of the 26 professional participants reported that their keypresses did not accurately represent discrepancies between what they would have intended and what they heard on Expert 2's recording[1]. After examining their mean rates of keypresses, we found these participants' responses were at or near the middle of the distribution of scores of other participants in their group listening to the same excerpt. We decided to leave these participants' keypress rates in the data set; their inclusion or exclusion does not affect the outcomes of the statistical analyses.

Sixteen participants indicated that they may have made one or two extra keypresses or indicated that they might have missed pressing the key once or twice. Some participants who commented about making extra keypresses reported they were sometimes overzealous in evaluating the performance; others volunteered that they simply pressed the key accidentally on several occasions. Participants who indicated they had missed keypresses reported that the practice was going too fast to catch every discrepancy, others noted they had forgotten to listen for 10-15 seconds, and others resisted pressing the key at the beginning in an effort to first understand what the performer was doing. Given the small numbers of keypress errors that these participants described, we allowed all of the data to remain in the data set as recorded.

When we examined the data, we noticed one participant's keypress record included 5 keypresses during the last second of the recording, though the most any other participant pressed the key was 3 times per second. We tried to duplicate this and determined that it was impossible to press the computer key this many times within a single second. We deleted four of these five keypresses from the data set.

[1] One professional indicated he was unsure if he was hearing repertoire in mixed meter or if the performer was practicing with irregular rhythms (though his assumption of irregular rhythms was accurate). Another expressed that the task was unlike practicing or teaching, where she would be able to stop herself or her student and thereby prevent many of the discrepancies she was hearing.

Some participants practiced pressing the key during the verbal instruction period or during the short breaks provided between excerpts. These keypresses, which were not linked to any recording, were not included in the data set.

Twelve participants volunteered that their keypresses were slightly delayed (i.e., they pressed the key after a few moments had passed since detecting the discrepancy). This was not surprising given the nature of the task. After a listener perceives a discrepancy between what they want and what they hear, it would take additional time to process the discrepancy and subsequently execute the keypress, resulting in an inevitable lag.

Mean Rates of Keypresses

We compared the mean rates of keypresses by student and professional participants using a two factor analysis of variance with repeated measures. We found that professional musicians marked significantly more discrepancies than did student participants, $F(1,48) = 11.13$, $p = .0016$, ($M_P = 15.04$ keypresses per minute, $M_S = 4.06$). There was no significant interaction between participant level and recording, $F(3,46) = 0.59$, $p = .63$. Professionals marked more discrepancies that did high school musicians in all four of the recorded excerpts (Student 1: $M_P = 15.61$ keypresses per minute, $M_S = 4.21$ keypresses per minute; Student 2: $M_P = 16.73$ keypresses per minute, $M_S = 4.21$ keypresses per minute; Expert 1 $M_P = 14.18$ errors per minute, $M_S = 3.22$ keypresses per minute; Expert 2 $M_P = 14.55$ keypresses per minute, $M_S = 3.96$ keypresses per minute).

Figure 4.2 shows the mean rates of keypresses among students and professional musicians listening to all four excerpts. Again, professional musicians pressed the computer key significantly more frequently than did student musicians while listening to all four excerpts, though there was a great deal of variability within groups.

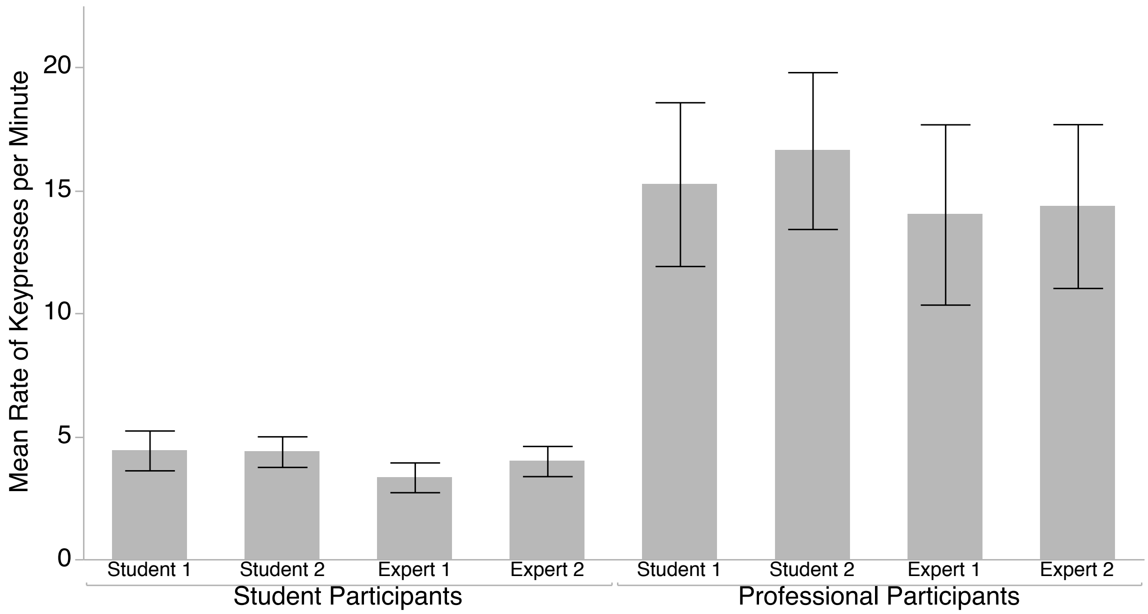


Figure 4.2. Student and professional participants' mean rates of keypresses in the four excerpts. Columns along the x-axis are divided into participant groups (students and professional participants), listening to each recording (Student 1, Student 2, Expert 1, Expert 2). Grey bars represent group means for each recording. Error bars constructed using ±1 standard error from the mean.

Listeners' Estimations of Performer's Level of Experience

We were also curious about how listeners' rates of keypresses were related to their perceptions of the performers' skill level in each recording. After participants listened to each excerpt, they estimated the experience level of the performer in the recording by selecting one of the following categories: high school musician, undergraduate music major, graduate performance major, or professional with an orchestra or university job.

In order to examine the relationship between participants' estimates of each practicer's level and the number of perceived discrepancies, we calculated the mean number of key presses for each estimate; that is, we calculated the mean for all of the test recordings that were thought to be made by a professional, a graduate student, an undergraduate, or a high school student. The data for this comparison are presented in Figure 4.3.

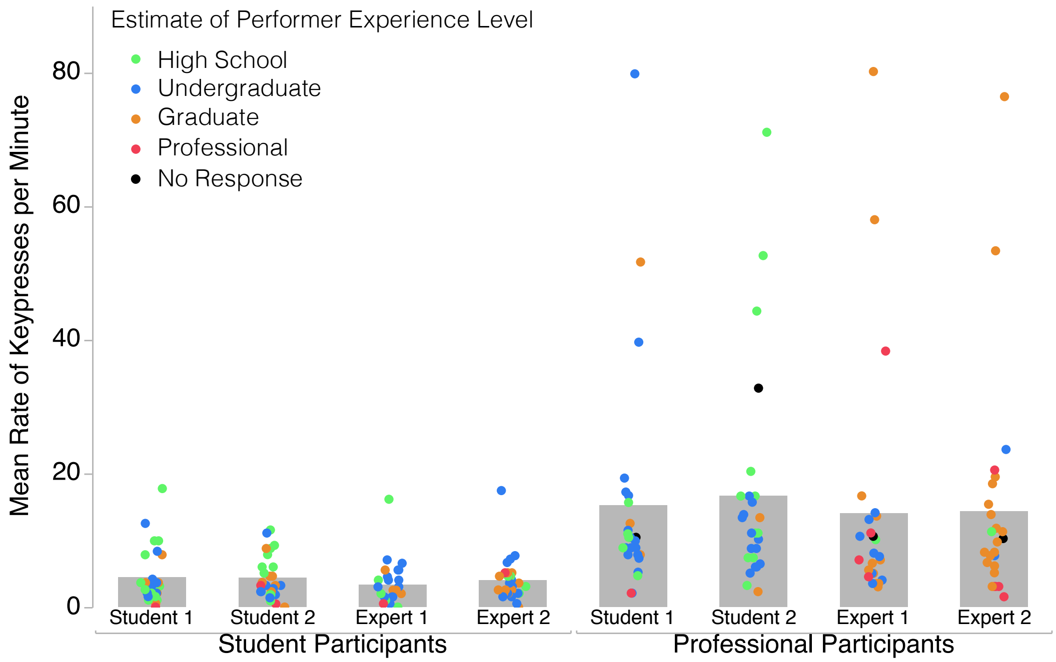


Figure 4.3. Participant estimates of performers' experience levels. Columns along the x-axis are divided into groups (students and professionals) and subdivided into excerpts (Student 1, Student 2, Expert 1, and Expert 2). Point position along the y-axis represent participants' mean keypress rates per minute while listening to each excerpt, point color represents participants' estimations of each performer's level of experience (high school, undergraduate, graduate, and professional).

Comparison of Violinists and Other String Players

Participants in the present study were violinists, violists, cellists, or bassists, all of whom listened to the same four audio recordings of four different violinists practicing. We were interested in comparing the rates of keypresses of violinists and other string players, as violinists would likely be more familiar with both the technical challenges and the repertoire represented on the recordings.

Nineteen of the 28 student participants and 13 of the 26 professional participants in this experiment listed violin as their primary instrument. Of the 9 student participants who were not violinists, 3 of them were violists (one of whom had previously played violin for 2 years), 4 were cellists, and 2 were bassists. Of the 13 professional participants who were not violinists, 6 were violists, 6 were cellists, and 1 was a bassist. One violist reported having played the violin "on and off," one reported having played violin for a year, one reported having played violin for 8 years, and one reported having played violin for 15 years. Because the latter two violists reported spending a great deal of time (8 years and 15 years respectively) playing the violin, they were included in this analysis as violinists.

We compared the mean rates of keypresses by violinists and other string players using a two factor analysis of variance with repeated measures. We found no significant difference between the mean rates of keypresses for violinists (M = 9.49) and other string players (M = 9.10), $F(1,48) = 0.01$, p = .91. There was a significant interaction between participant instrument and recording, $F(3,46) = 2.85$, p = .05. Violinists marked fewer discrepancies that did other string musicians while listening to both recordings of student musicians (Student 1: M_V = 9.25 keypresses per minute, M_O = 10.33 keypresses per minute, Student 2: M_V = 9.74 keypresses per minute, M_O = 10.94 keypresses per minute), and violinists marked more discrepancies than did other string musicians while listening to both recordings of professional musicians (Expert 1: M_V = 9.24 errors per minute, M_O = 7.34 keypresses per minute, Expert 2: M_V = 9.93 keypresses per minute, M_O = 7.72 keypresses per minute).

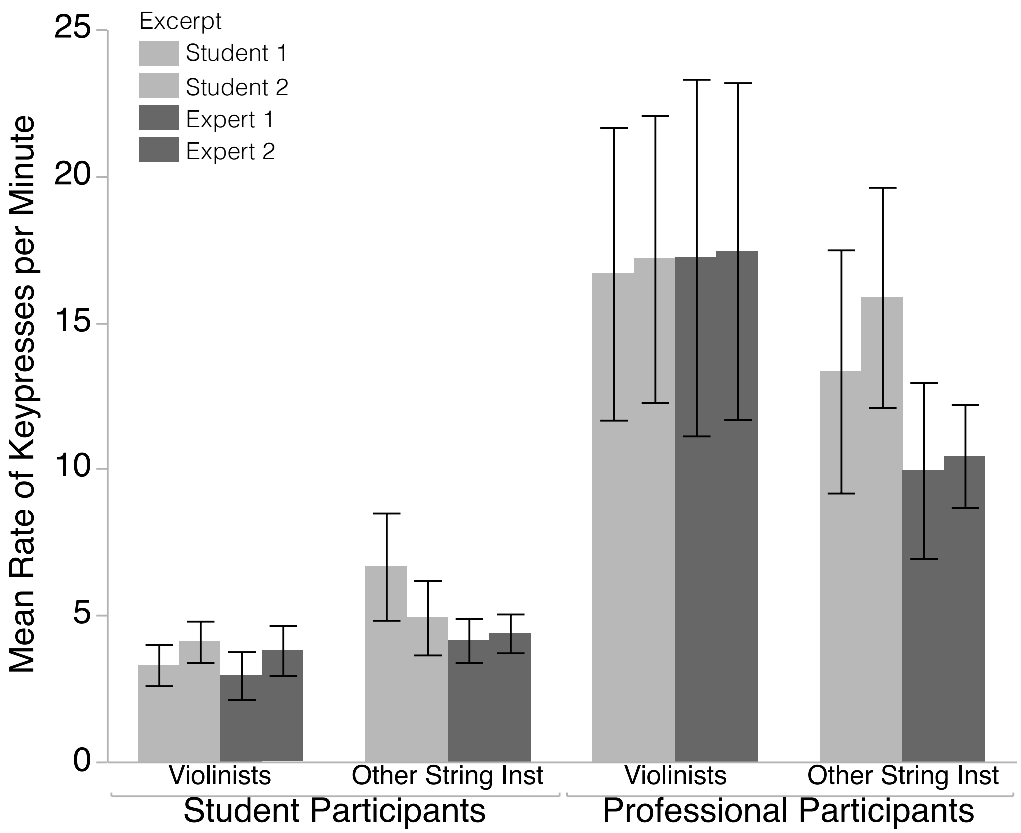


Figure 4.4. Keypress rates by participant instrument. *Note*. Columns along the x-axis are divided into two groups (violinists and non-violinists) and two sub groups (students and professionals). Grey bars represent group means for each auditory excerpt (Student 1, Student 2, Expert 1, Expert 2). Error bars constructed using ±1 standard error from the mean.

Participant Familiarity with the Task

Thirteen of the 28 student participants and 11 of the 26 professional participants had participated in Experiments 1 and 2 prior to participating in the present study. We compared the rates of keypresses for returning participants, who had performed the same procedure while listening to their own practicing, to the keypress rates of participants who had never completed the task before.

We compared the mean rates of keypresses of returning participants and new participants using an independent-samples *t*-test. We found no difference in mean rates of keypresses between returning participants (M = 9.88, SD = 14.95) and new participants (M = 8.92, SD = 10.95), $t(52) = 0.27$, $p = .79$. In Figure 4.5, we present the mean keypress rates for new and returning participants. Returning participants who had completed a similar task while listening to their own practice recording pressed the computer key as often as participants who were new to the task.

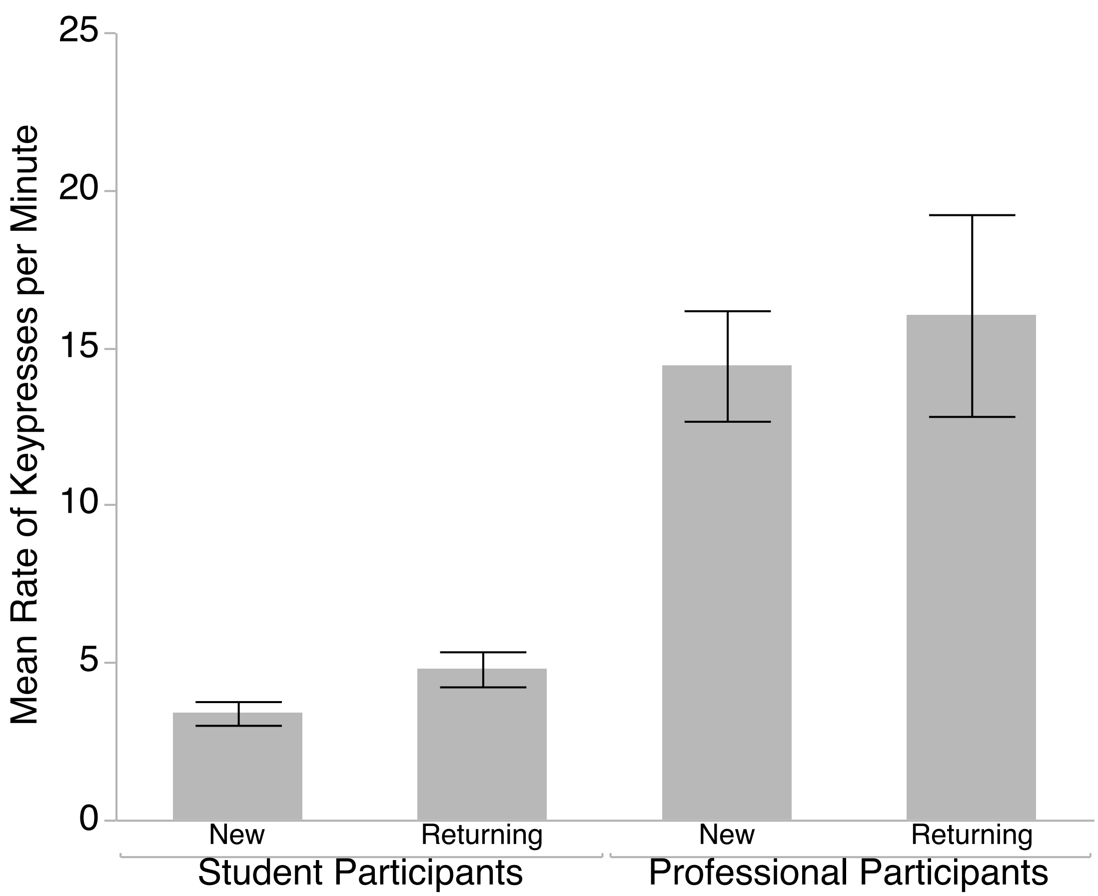


Figure 4.5. Keypress rates for new and returning participants. The x-axis is divided into groups (new and returning participants) and two subgroups (students and professionals). Error bars constructed using ±1 standard error from the mean.

Types of Perceived Discrepancies

Participants described the types of discrepancies they heard on the recording, and we coded each participant's comments according to the categories they mentioned; most participants made comments in two or more categories. The numbers of discrepancies of each type in each experience category are presented in Table 4.2.

Table 4.2

Number of Participants Commenting about Each Type of Discrepancy by Excerpt

	Type of Discrepancy					
Excerpt	Intonation	Tone	Practice	Expression	Timing	Notes
Student Participants (*n* = 28)						
Student 1	22	20	7	12	6	0
Student 2	23	12	16	9	9	3
Expert 1	23	14	17	14	3	8
Expert 2	21	12	11	4	4	4
Professional Participants (*n* = 26)						
Student 1	13	19	3	7	8	0
Student 2	25	11	5	4	8	1
Expert 1	16	11	6	4	3	6
Expert 2	18	11	7	0	10	2

Note. The number of student and professional participants who mentioned each type of discrepancy (intonation, tone, notes, expression, timing, practice) by excerpt. Most participants identified more than one type of discrepancy.

Timing of Perceived Discrepancies

We examined individual participants' patterns of keypresses. Timelines of each participant's keypresses are displayed in Appendix D. Each row represents the sequence of keypresses by a single participant. Participants are grouped by experience level (student and professional) and, within each group, are arranged in order by number rate of keypresses. Some participants consistently pressed the key throughout the 2-min practice excerpt, whereas others had bursts of keypresses. There are many moments when professional and student participants all tended to press the computer key, most often when the performer abruptly stopped to correct an error during practice. There is much less agreement between professionals and student participants during moments when the performer played through a passage without stopping.

DISCUSSION

Our results indicate that the numbers of discrepancies participants perceive in other musicians' practice sessions differ significantly between student and professional musicians. When student musicians and professional musicians marked moments of discrepancy between what they would have intended if they were the performer on the recording and what they heard while listening to other musicians practicing, professional musicians pressed the key more frequently than did student musicians. This was true whether participants were listening to recordings of student or professional players.

This finding is consistent with our initial hypothesis, that as musicians develop expertise, increasing levels of auditory and physical discrimination shift intentions and expectations toward clearer and more refined goals. Experienced performers with highly developed auditory discrimination and precisely defined musical intentions more readily perceive small variations from those goals when they occur. This behavioral finding is consistent with the current understanding of motor skill learning. When learning to execute highly complex motor skills with accuracy, learners must perceive discrepancies between intentions and outcomes. Novice learners might be satisfied with notes that initially land out of tune as long as they are quickly adjusted before the next note, whereas more experienced players come to expect every note to begin and end precisely in tune. Still more experienced players might come to expect their finger to follow such a precise trajectory that even small discrepancies in the path are perceived as discrepancies between intent and outcome, even if the trajectory is corrected *en route* and ultimately lands in the correct location (Maidhof, Pitkäniemi, & Tervaniemi, 2013).

Perhaps the progression from novice to expert is not best characterized as a reduction in error making, but rather as an increase in the elaboration and precision of tangible goals and the ability to perceive more nuanced discrepancies. This hypothesis is supported by the keypress rates among professional and student participants, and was also evident in some participants' responses to the question of whether their keypresses accurately reflected what they perceived. One student participant pressed the key 4.5 times per minute while listening to the recording of Expert 1. Afterward, when asked to identify the nature of the discrepancies she perceived, she commented, "There were out of tune notes which they fixed quickly, so I couldn't count most of those. So, it was mostly just a tone thing on the string crossings." For this participant, a note that initially lands out of tune but is subsequently adjusted was not a discrepancy between what she wanted and what she heard.

A professional participant listened to the same excerpt and pressed the key 13.1 times per minute. Afterward, when identifying the nature of the discrepancies she perceived, she stated, "Intonation. They'd get it right by sliding up to the pitch of course, but then they moved on rather than really finalizing it so [their finger] would land in tune. [There were] tone issues as well around the string crossings." For this participant, an adjusted note was a discrepancy between what she wanted and what she had heard on the recording. Because her definition of "in tune" was more refined, she also noticed another type of discrepancy—that the performer was practicing adjusting her fingers when they landed in the wrong place and was not practicing dropping her fingers in the correct place to get the beginning of the note in tune.

In this example, the student participant perceived small errors in pitch, though she did not identify these moments as discrepancies between what she would have intended and what she heard. The professional participant acknowledged that the pitches were corrected, but identified these moments as discrepancies between what she would have intended and what she heard. This difference in thinking has profound implications for learners embarking on self-directed practice. Learners who hear themselves slide up to pitch and think, "Nailed it! I just had to slide a little bit." are in a different position than learners who hear themselves slide up to pitch and think, "Doh! I barely made that one."

Both the student participant and the professional participant described above were capable of perceiving the slides up to pitch in this instance, though only the experienced participant identified the quickly-corrected pitches as discrepant from her intentions. The more experienced participant had a different standard of acceptability. *Of course* she would adjust pitches that were out of tune, but even after the adjustment was made, those pitches would prompt additional attention during practice. If these two participants had been practicing this excerpt themselves, it is reasonable to expect they would emerge with different results even if the student had spent much more time practicing. Learners are only in the position to practice like their teacher when they perceive discrepancies like their teacher.

The keypress task used in the present study measures the rate of perceived discrepancies between what a listener would have intended and what they heard; it was not a measure of what participants heard when they did *not* press the key. Not pressing the key in response to a performance error on the recording may be an indication that the participant did not perceive the error at all, or an indication that the magnitude of the error was too small to be considered a discrepancy between intentions and outcomes.

Future research should investigate the extent to which novice musicians can perceive within contextualized musical examples the same differences in pitch, inflection, and tone that are perceived by more experienced musicians. This question has broad implications for teachers working to help learners identify the same discrepancies that they identify.

Two competent high school aged violinists and two expert violinists with extensive performing and recording accomplishments performed the excerpts we used as auditory stimuli for the present study. The rate of keypresses varied systematically for *listeners* at different levels of experience and expertise, but neither professionals' nor students' keypresses varied systematically for *performers* at different levels of experience and expertise. Listeners at both levels of skill development heard as many discrepancies in the playing of expert violinists as they heard in the playing of student violinists.

It is interesting to note that experienced participants' rates of keypresses while listening to their colleagues was similar to their rate of keypresses while listening to performers at a level they would typically teach. These skilled listeners approached the keypress task with such clarity and precision regarding their own performance goals that even small discrepancies from their refined expectations would be readily noticed.

We asked participants to estimate the level of the performer they heard on each recording. Student participants had more difficulty accurately estimating the experience level of the performers on the recordings than did professional participants, which is perhaps not surprising. Professional musicians' experience developing their own skills would undoubtedly inform their evaluations of others' playing. It seems important to emphasize, however, that professional participants' perceptions of each performer's level was independent of their rate of keypresses or the types of errors they described. The experienced listeners pressed the key at similar rates regardless of whether they were listening to someone they thought was a high school student or someone they thought was a graduate student.

One professional participant, an outlier in the current study, pressed the key 80.2 times per minute while listening to Expert 1. He marked 159 moments of discrepancy between what he would have intended and what he heard, noting errors in tone production, character, intonation, coordination of left and right hand, shifting sounds, finger placement, and a portato [pulsating] sound. Yet, after listening to the excerpt, he commented that the performer had a "very mature sound." Although this participant marked a large number of discrepancies, he nevertheless recognized the quality of the performer's sound.

Another highly skilled professional participant first listened to Expert 1 and then listened to Student 1 without knowing, of course, that one was his colleague and the other was a high school student. When asked about the nature of the discrepancies he perceived in the second (the student's) recording he commented, "It was all the same stuff [as Expert 1's recording]. This player had less physical control from finger to finger in their left hand and also how they moved from string to string with their bow. All the same issues exist as the previous excerpt, but they [the issues] are much more exaggerated in this one, whereas the other one was much more refined." When prompted to elaborate on the "exaggeration" or "refinement" of the discrepancies he commented, "The intonation errors were bigger, there was more margin of error. The bow changes were sloppier. While there were bow speed issues in the first clip, they were exaggerated in this one."

In terms of the number and type of discrepancies he heard, the student's playing was "all the same" as the expert's playing, though the magnitudes of the discrepancies were entirely different. Although this listener was fully capable of accurately estimating each performer's level of experience, his rate of keypresses and the types of discrepancies described did not clearly distinguish between the competent learner and the skilled expert. This is interesting to think about within the context of contest adjudication and student evaluations, which often focus both listeners' and learners' attention toward the number and type of errors a skilled listener perceives in the performance of a learner. Perhaps evaluative measures that focus listeners' and learners' attention toward the level of refinement represented within a performance or a recording would more accurately convey to learners the differences between highly skilled and novice performers.

Of course, professional participants may well have relied on the repertoire played on the recordings as a clue to determine the levels of the performers. Several professional participants commented that since the student performers were working on concertos by Lalo and Bruch (pieces typically found in pedagogical sequences, though still occasionally performed outside of pedagogical contexts), that they were likely high school students or undergraduates. Similarly, several high school students commented that since they had worked on these pieces themselves, the performers must have been at about their level. Future research asking listeners to distinguish between highly skilled performers and novice performers playing pieces typically found in pedagogical sequences could examine the extent to which the performers' repertoire factors into listeners' evaluation of the performer's level.

We noted previously the high variability within participant groups in the rates of keypresses, an observation that is perhaps unsurprising given the results of Experiments 1 and 2. As in both of the previous studies, participants' interpretations of the task potentially influenced their rates of keypresses across all four excerpts. For example, one participant who perceives an intonation error over three consecutive notes might mark that moment with three distinct keypresses, whereas a different participant might mark the moment with one keypresses to represent the larger error—a misplaced hand that caused three out of tune pitches.

In the present study, all participants listened to all four excerpts, and thus small differences in the interpretation of the task would be equally represented in the mean keypress rates across all four recordings. Indeed, there is a great deal of individual consistency in keypress rates across all four excerpts. Given the nature of the task and the design of the study, this within-group variability did not seem problematic.

It is interesting to note, however, that both student and professional participants' mean rates of keypresses were higher while listening to the practice excerpt than they were during any of the four test recordings. The practice recording contained salient intonation errors; the violinists' finger often landed extremely sharp or flat and remained there throughout the duration of the pitch.

The timeline of individual participants' keypresses reveal that professional and student participants had moments of general agreement in pressing the key, most often when the performer on the recording abruptly stopped or repeated a passage. As one professional participant noted after listening to Expert 1, "They are making corrections and stopping sometimes, so you kinda have to press when they go back for stuff. You're on task with them because they are deciding when to stop and when to go on." There is much less agreement on when to press the key when the performer is playing through a passage without stopping. It seems reasonable that students would more heavily rely on the performer stopping to indicate errors in the performance and musicians with more experience would more heavily rely on their own internal model to evaluate the recording.

Some professional participants volunteered that, as they were making comparisons between what they would have intended and what they heard on the recordings, they were adjusting their concept of the practicer's goal (e.g., let articulations go to focus on intonation) or their mental image of the goal within the context of what the practicer was focused on. On professional musician commented, "I wasn't quite sure about their goal. I might have pressed it more often but I was waiting to figure out what their goals were." Another commented, "I let stuff go toward the end. I was really taking context into consideration which is easier to do when it's not such manic practice."

Another professional participant commented about the juxtaposition of being on task with the performer, and what she would normally do in her own practice or her own teaching. When asked if her keypresses accurately reflected what she heard, she commented, "Probably not, because what was going on was not something where you can direct what was happening. If I was teaching them, I would have had them stop a long time ago… and then we would have progressed with a particular program. It's just seemed really random. It's hard to know what am I pressing for. Sure, I wouldn't have liked [the sound coming from the instrument], but really I would have stopped them so long ago. So, I just kept hitting [the key] whenever I went, 'Well that was pretty bad and you didn't stop.'"

This thinking is largely consistent with behavioral studies of music practice which have found that highly skilled learners stop in anticipation of mistakes and systematically vary the tempo to elicit more accurate playing (Duke et al., 2009). Because this professional participant was unable to control the task as she would during her own practicing or teaching, she felt the rate of discrepancies she identified on the recording would be much different from the rate of discrepancies she would hear in her own practicing and teaching. Skilled musicians can manipulate the context and the task to address and manage existing errors and to systematically reveal potential moments of error to themselves. Learners who use practice time to systematically control the rate of discrepancies are in a different position to practice than are learners who use practice time to merely respond to discrepancies.

Results from the current study suggest that musical expertise is not best characterized as a reduction in the rate of error making, but rather a refinement of tangible goals. As learners progress through the various stages of musical development, they must come to define increasingly precise performance goals and to make increasingly fine discriminations about auditory and physical discrepancies between those goals and the sounds and movements they produce.

Chapter V: Discussion

Errors are an inherent and necessary part of learning for musicians at all levels of experience and expertise. To effectively encode and refine procedural memories, leaners must make attempts toward well defined goals, perceive discrepancies between the outcomes of their attempts and what they intended to do, and subsequently modify their behavior to accommodate those discrepancies both during movement and in future attempts (Wu et al., 2014). The processes involved in music practice epitomize these central features of skill learning. Thinking about errors in terms of discrepancies between intentions and outcomes has important implications for musicians engaged in practice, as the clarity of a performer's intentions necessarily determines the performer's self-perceptions of accuracy in fulfilling those intentions.

This investigation is the first to examine how musicians' perception of errors as discrepancies between intentions and outcomes changes for learners at different levels of experience and expertise. Perhaps the most important finding of this study is that as musicians develop expertise, they develop increasing levels of auditory and physical discrimination that then shift their intentions and expectations to increasing motor refinement and clarity and precision in goal setting.

The discussion below addresses this finding as it relates to the following topics:

1. Development of Musical Expertise
2. Applications for Teachers and Learners
3. Questions Resulting from this Investigation

DEVELOPMENT OF MUSICAL EXPERTISE

The development of music performance skills requires the refinement of both motor behavior and perceptual skills through an iterative process of goal setting, performance, and self-evaluation. Many novice learners seem to believe that as they progress through years of deliberate practice, they will commit fewer and fewer errors over time. It is certainly the case that artist-level performers make few noticeable errors in public performances, but the quality of these performances is in many ways dependent upon the many discrepancies (errors) that artists committed, identified, and corrected during practice.

Technical facility and musical artistry require the formulation of vividly clear performance goals and high levels of auditory and physical discrimination. Put more simply, artist-level performers have a precise idea of what they want and acutely detect discrepancies between their goals and what they do moment to moment. After eliminating most of the discrepancies encountered during practice, artist-level performers are able to play in a way that may seem flawless to even the most avid listeners. In this sense, learning to practice effectively seems better characterized not as a decrease in error making but as an *increase* in intentional clarity and perceptual acuity.

This is consistent with a feed-forward model of motor control originally suggested by Robinson (1973), which hypothesized that the CNS compares efferent predictions to afferent sensory feedback, weighing these variables with regard to uncertainty. Discrepancies between what was expected and what is experienced signal a prediction error, which updates the motor command through a process mathematically represented by the Kalman filter (Kalman, 1960). In order to update a motor command, learners must perceive discrepancies between their intentions and outcomes.

In Experiments 1, 2, and 3, we examined musicians' perceptions of their own practice and others' practice by asking them to press a computer key to mark moments of discrepancy between what they had intended and what they heard. In Experiment 1, we asked participants to do this while listening to their own practice; in Experiment 2 we asked participants to do this while listening to their own practice two years after they had recorded it; and in Experiment 3 we asked participants to do this while listening to four other violinists practice (two highly skilled experts and two competent students).

It is important to note that in all three instances, participants' keypresses represented moments of discrepancy between what they wanted and what they heard; each participant's keypress rates were wholly dependent upon each participant's concept of the goal at the time they were completing the keypress task. Participants always determined for themselves what qualified as a discrepancy, and the keypress rates measure the frequency at which the recording did not meet their expectations.

In Experiment 1, participants listened to a recording of themselves practicing immediately after recording it. This design allowed us to examine musicians' perceptions of their own work, making comparisons between high school students, undergraduates, graduate students, and professionals. We found that the number of discrepancies participants perceived did not vary systematically for listeners at different levels. Although there were high within-group variances in the rates of keypresses, overall, highly skilled musicians perceived discrepancies in their own practice as frequently as did developing musicians. These results are not consistent with the idea that as musicians progress through years of deliberate study they progress toward error-free playing, but rather, that as musicians gain experience, their expectations shift toward more refined, artistic goals.

In Experiment 2, the high school and professional participants from Experiment 1 returned approximately 2 years later and completed the keypress task while listening to their 2-year-old practice recording. This allowed us to ask whether student and professional musicians' perceptions of their own work change with the passage of time. Developing musicians did indeed demonstrate evidence of refined expectations; after 2 years, students identified many more moments when their recording did not meet their expectation than they had 2 years earlier when they first made the recording.

In Experiment 3, student and expert musicians listened to practice recordings made by four violinists (two competent high school students and two highly skilled experts). The design of Experiment 3 allowed us to make comparisons between what musicians at different levels of experience perceive while listening to excerpts of other musicians' practice. The professional musician listeners identified significantly more discrepancies than did the high school musician listeners in all four of the test recordings, but there were no significant differences in the rates of keypresses among the four recordings for either group of listeners; that is, professional and high school musicians perceived similar numbers of discrepancies regardless of whether they were listening to practice recordings of competent high school players or professionals.

When taken together, results from Experiments 1, 2 and 3 indicate that two important variables, the clarity of musical intentions and perceptual acuity, differentiate artist-level musicians from less experienced musicians. This seems especially notable in light of the fact that music performance instruction at all levels seems to focus primarily on what musician's *do*, and not on what musicians *intend to do* and what musicians *perceive about what they do*. Thus, a major impediment in developing skill is learners' ability to know precisely what they intend to do and to know precisely whether they actually have done it.

It is understandable that the beginning stages of skill development in any domain must focus initially on learners' reaching approximations of what will ultimately become highly refined movements. But how learners define goals and focus attention have everything to do with the effectiveness of practice over time, and directing learners' attention to defining goals and evaluating performance outcomes is the purview of the teacher. The goal of moving the bow, for example, may focus only on the bow arm, where the bow contacts the string, and the angle of the bow relative to the string. But this movement not only produces proprioceptive, haptic, and visual feedback, but auditory feedback (the ultimate goal of the bow movement) as well. If novice learners remain focused on the movements themselves, rather than the sounds those movements produce, it is understandable that their progress will be limited compared to that of novice learners who focus also on the sound of the instrument.

Novice learners embarking on their musical studies often expect to play increasingly difficult repertoire over time, but more important is an understanding that over time they will develop increasingly more refined artistic expectations. Common aphorisms like *Perfect practice makes perfect* imply that flawless performance requires practice time filled with flawless repetition, but perhaps the progression from novice to expert is not best characterized as a reduction in error making, but rather as an increase in the clarity of artistic goals and the ability to perceive more nuanced discrepancies between those goals and performance outcomes. What varies among the performances of novices and experts is often more than the number of errors that occur, but rather the depth of what musicians hear, which in turn informs what they do.

APPLICATIONS FOR TEACHERS AND LEARNERS

Our results suggest that as musicians learn over time, increasing levels of auditory and physical discrimination shift performers' intentions and expectations to increasing levels of refinement. Experts' perception of discrepancies between intentions and outcomes reflect clearer intentions, more vivid expectations, and finer levels of discrimination than are defined by less skillful players.

A novice learner, whose intention is merely to remember the c-natural, is poised to experience a prediction error ("oops!") if he accidentally plays a c-sharp. A different learner, whose intention is to play a beautifully inflected c-natural with wide vibrato and heavier bow weight, is poised to perceive a discrepancy if she accidentally plays a c-sharp, if her vibrato is too narrow, or if her bow weight is too light. Learners with more precise and elaborate expectations obtain more information with each repetition because the discrepancies between the intention and the outcome are more starkly apparent. The effectiveness of practice, it seems, is heavily dependent upon what the learner perceives as a discrepancy.

Our results contribute not only to the formulation of a model of expertise in music performance, but also to pedagogical practice. Music teachers often set goals of giving clear instructions and pointed feedback (telling) intended to modify various aspects of their students' playing. Equally important, though, is *asking* learners to think carefully and explain clearly their intentions about what they set out to accomplish in each performance trial. For students to practice like their teachers, they must establish a level of acceptability for their own playing that is consistent with their teachers' refined, artistic image and subsequently perceive small discrepancies between what they are doing and this artistic image.

This was evident in the interviews of Experiment 3, when both a student participant and a highly skilled expert participant noticed the performer on one of the recordings was adjusting her intonation as she was playing. The developing musician did not mark these moments as discrepancies, mentioning that the performer adjusted her intonation. The highly skilled expert noted that *of course* the performer adjusted her intonation but still marked the moments as discrepancies, noting that the performer never went back to practice getting these notes to *land* in tune. This difference in thinking has profound implications for learners embarking on self-directed practice. If these two participants were practicing these excerpts themselves, it is reasonable to expect they would accomplish a different standard of intonation regardless of how much time either participant spent practicing.

The level of refinement within learners' artistic image will change how learners progress through self-directed practice. Music teachers often suggest common practice tools to aid students in reaching goals (e.g., slowing down, using a metronome, or practicing running 16^{th} notes in altered rhythms), but learners must be able to perceive small differences between what they are doing and what they want to be doing *as* they deploy these practice tools in order to render them effective.

When expert learners work on a shift in a slower tempo, for example, it is to reveal where in the shift their finger's trajectory goes off course. When expert learners practice with a metronome, it is to reveal where the tempo begins to rush. When expert learners alter the rhythm of a fast 16^{th} note passage, it is to reveal which fingers are landing too fast or too slow and causing the passage to become uneven. Experts *use practice tools to strategically reveal errors* during practice, but practice tools are only effective if learners perceive discrepancies between what they are doing and what they want to be doing as they are using them.

Learners are only in a position to practice like their teacher when they have an accomplishable, crystalized image of artistic excellence as an expectation for their own playing. *This* should be a primary goal in lessons and rehearsals. Teachers' expectations for learners are not static, and learners' standards of acceptability for themselves should not be static either. It certainly may be appropriate for a developing musician's proximal goal to be to quickly adjust errant notes, but this is only a proximal goal. Eventually, learners' expectations shift toward a more refined goal—getting the note to land in tune.

This is not only true with technical goals, but also with musical goals. A student with an expressive opening to a Mozart concerto in high school can develop into a graduate student with more refined bow changes and a continuous vibrato that allows him to seamlessly connect the notes in the same opening and create a more refined musical line. As musicians develop expertise, their expectations should become more refined as well.

This raises an important issue about musical development, namely, that a major inhibitor of learners' progress is a lack of precise and increasingly elaborate goal setting. The motor system can obtain only as much information from a given movement as the movement's goal is clear in the mind of the learner. The more refined the goal, the greater the opportunity to gather information from the outcome of the movement.

Lev Vygotsky (1978) discussed this in his concept of the Zone of Proximal Development, which he defined as the difference between what learners can do on their own through independent problem solving and what they can do in collaboration with teachers and peers. Learners who can perceive discrepancies between what they do and what an expert would do are capable of engaging in independent practice that would propel them toward becoming an expert. Learners who do not yet perceive these discrepancies need peers or teachers to mark moments of discrepancy for them, lest more nuanced discrepancies between what they are doing and more precise and elaborate goals go unnoticed.

Teaching that leads to effective practicing is teaching that systematically reveals discrepancies to learners over time, such that what learners come to expect is what their teachers would come to expect. Asking learners to think carefully and explain clearly their intentions about what they set out to accomplish in each performance trial provides opportunities for learners to experience practicing like an expert. Importantly, as learners do so, they reveal their concept of an acceptable artistic image in a way that allows teachers to help them refine that concept over time.

Teachers often strive to minimize or eliminate student errors, thinking that if students only complete accurate repetitions in the presence of their teachers they will not accidentally produce inaccurate repetitions on their own. Yet, variability (error making) early in learning is advantageous. When Wu, Miyamoto, Castro, Ölveczky, and Smith (2014) asked participants to manipulate a lever attached to an arm in an effort to move the arm along a target trajectory, early variability, which produced greater movement error, was not detrimental to learning, but instead predicted faster learning. When Chen and colleagues (Chen et al., 2013) examined expert cellists' finger movements, they found that highly skilled cellists quickly made adjustments that rendered their errors imperceptible to listeners. Indeed, the ability to adjust is an important aspect of performance.

The problem with persistent inaccurate playing is that the sensorimotor system habituates to the repeated inaccuracies and comes to hear inaccuracies as being accurate. When learners form consistent associations between what they do physically and the outcomes of their movements, even if those outcomes is not uniformly accurate, they develop a level of motor control that is impossible to obtain without experiencing discrepancies between intentions and outcomes.

Asking students to articulate the differences they hear between repetitions and to explain the connections between the movements they make and the sounds they produce focuses learners' attention toward the types of associations that predict faster learning. A comment from one expert cellist after he completed Experiment 3 is apropos. When asked how he came to perceive smaller and smaller discrepancies he said, "For me, it was from playing in a quartet and being immersed in the sound in the quartet, and then [during rehearsal] going out into the hall to hear my colleagues play and hearing the sound from that perspective. We'd take turns making small changes and then seeing what we could hear in the hall. There's something in that comparison, in knowing the piece so well and hearing that comparison. Then, making decisions about what to do and hearing how those decisions affect the sound. That process really makes you start to hear differences."

QUESTIONS RESULTING FROM THIS INVESTIGATION

The keypress task used in Experiments 1, 2 and 3 was intended to record instances when a practicer's performance on a sound recording did not meet participants' expectations, whether it was a contemporaneous recording of the participants themselves, an old recording of themselves, or a recording of another musician. Of course, we cannot make any assertions about what participants perceived at moments when they did *not* press the key, which may indicate that participants did not perceive a discrepancy, or that the magnitude of a perceived discrepancy was too small to be considered a problem. Learners who perceive an error but identify it as acceptable are in a different position than learners who do not perceive an error at all.

Future research should investigate the extent to which novice musicians and professional musicians perceive the same differences in pitch, inflection, and tone within contextualized music examples. This question has broad implications for teachers working with learners to help them plan, execute, and hear more like their teachers.

In all three experiments, we observed a great deal of variability in the keypress rates among participants within each group. It is notable that in Experiment 1, when participants were listening to themselves practicing a piece of their choice, the rates of keypresses were unrelated to how long participants' had been working on their pieces. Similarly, keypress rates were not related to whether participants were relearning a piece that they had preformed previously. The ratio of each participant's repertoire level relative to their skill level seems like a probable source of variability, as does the length of time participants had been working on the repertoire they brought to the testing session, but the data were not consistent with these possibilities. This finding certainly warrants further attention.

It is perhaps unsurprising that both highly skilled experts and competent learners addressed pitch accuracy in their own playing and the playing of others; string musicians deal with several sources of variability in their intonation. Each finger must be positioned precisely on the fingerboard, with very little tolerance for positional errors, but there is also a great deal of variability among string players in selected fingerings. Ill-fitting or poorly practiced fingerings can become an undesired source of intonation variability, even among highly skilled performers, whereas well thought out and practiced fingerings provide a source of artistic variability that provides string musicians opportunities to make individual artistic choices.

Intonation is an interesting and useful framework for future investigations into musicians' perceptions of errors, one that provides both visual and auditory information about learning as movements unfold. For any given pitch, there are two measurements that can represent learning: the initial landing position as determined by the note onset pitch and the speed of correction as determined by pitch adjustment. It is possible to force intonation errors even among highly skilled performers by asking participants to use an unusual fingering within a framework that provides an ongoing feedback loop to participants. While Maidhof (2013) has examined prediction errors within the context of discrete errors on a piano keyboard (errors that cannot be corrected once the movement has occurred), future investigations examining string intonation may shed additional light on the role of prediction errors in control of ongoing movements.

CONCLUSION

With respect to practice sessions, the progression from novice to expert is not characterized primarily by a diminution in the rate of error making, but rather by an apparent *increase* in the precision and elaboration of intentions and expectations. As musicians develop expertise, their standards of acceptability become increasingly more refined, which in turn leads to successful attempts toward increasingly more refined tangible goals. It is not simply that expert musicians make fewer errors, but that they have a rich and vivid standard of acceptability along with the perceptual skills to perceive very fine discrepancies between these refined intentions and the outcomes of their movements, an important message for developing musicians to understand.

Appendix A: Experiment 1—Consent and Assent Forms

IRB USE ONLY
Study Number: 2014-06-0046
Approval Date: 08/05/2015
Expires: 08/04/2016

CONSENT FORM

You are being asked to participate in a research study that is being conducted by The University of Texas at Austin. Please read the information below and feel free to ask questions before you decide if you would like to participate.

Title. How did I do? Musicians' self-perceptions of performance during individual music practice.

Principal Investigator. Robert A. Duke, Ph.D.
Professor of Music and Human Learning
Butler School of Music, The University of Texas at Austin
512-471-0972, bobduke@austin.utexas.edu

Research purpose. You have been asked to participate in a research study about music learning. The purpose of this study is to examine the relationship between auditory discrimination and the execution of physical skill by accessing musicians' perceptions of their own playing.

Experimental procedure. If you agree to participate, you will be video recorded while warming up for 2 minutes, and practicing a brief excerpt on your primary instrument for 5 minutes. Afterward, you will be asked to review the audio portion of that recording and identify moments when the outcome is different from what you intended by pressing a button on a computer keyboard. At the end of this process, you will be asked four questions about your experience. The study will take 20 minutes to complete.

Benefits. You will not receive any direct benefit from participating in this study; but the results will contribute to our understanding of human learning and musical skill development.

Risks. There are no foreseeable risks to participating in this study.

Compensation. You will not receive any compensation for your participation.

Participation. Your participation is voluntary, and you may withdraw from this study at any time. You may also refrain from answering any question asked of you for any reason. These choices can be made without penalty or loss of benefits to which you are otherwise entitled and without jeopardizing your standing with the University of Texas at Austin.

The University of Texas at Austin — Page 1 of 2
Institutional Review Board – Revised July 2013

Data confidentiality. All research data is confidential and will not be linked to your identity. All research records will be locked in the principal investigator's office for the duration of the data collection and analysis. Only the principal investigator and one graduate assistant will have access to your data, and both have completed training in research with human participants. Your data may be used in publications and/or presentations but your identity will not be disclosed.

If you choose to participate in this study, you will be video recorded. Any video recordings will be store securely and only the research team will have access. Recordings and data will be kept for 2 years and then erased.

If it becomes necessary for the Institutional Review Board to review the study records, information that can be linked to you will be protected to the extent permitted by law. Your research records will not be released without your consent unless required by law or court order. The data resulting from your participation may be made available to other researchers in the future for research purposes not detailed within this consent form. In these cases, the data will contain no identifying information that could associate it with you, or with your participation in any study.

Questions. If you have questions prior to, during, or after participating in this study, please contact the primary investigator using the contact information listed at the top of this form. Questions or concerns about the research, research participants' rights, and/or research-related injuries to participants should be directed to the Institutional Review Board. You can contact them by phone at 512-471-8871 or email at orsc@uts.cc.utexas.edu.

Results. If you would like to receive the results of this study, please indicate your email address or other contact information below:

Contact Information:____(optional)

Signature. You are welcome to ask questions before or after signing this form; and by singing it, you are not waiving any of your legal rights. You are able to withdraw from the study at any time without penalty.

____ _______________________
Signature of Participant Date

____
Printed Name of Participant

____ _______________________
Signature of Person Obtaining Consent Date

____
Printed Name of Person Obtaining Consent

IRB STUDY NUMBER: 2014-06-0046

Parental Permission for Children Participation in Research

Title: How did I do? Musicians' self-perceptions of performance during individual music practice.

Introduction

The purpose of this form is to provide you (as the parent of a prospective research study participant) information that may affect your decision as to whether or not to let your child participate in this research study. The person performing the research will describe the study to you and answer all your questions. Read the information below and ask any questions you might have before deciding whether or not to give your permission for your child to take part. If you decide to let your child be involved in this study, this form will be used to record your permission.

Purpose of the Study

If you agree, your child will be asked to participate in a research study about music learning. The purpose of this study is to examine the relationship between auditory discrimination and the execution of physical skill by accessing musicians' perceptions of their own playing.

What is my child going to be asked to do?

If you allow your child to participate in this study, they will be

- Video recorded while warming up for 2 minutes

- Video recorded while practicing a brief excerpt on his or her primary instrument for 5 minutes.

- Asked to review the audio portion of that recording and identify moments when the outcome is different from what he or she intended by pressing a button on a computer keyboard.

- Asked four questions about his or her experience.

This study will take 20 minutes and there will be a total of 60 people in this study. Please note that your child will be video recorded during this study.

What are the risks involved in this study?

There are no foreseeable risks to participating in this study.

What are the possible benefits of this study?

Your child will not receive any direct benefit from participating in this study; but the results will contribute to our understanding of human learning and musical skill development.

Does my child have to participate?

No, your child's participation in this study is voluntary. Your child may decline to participate or to withdraw from participation at any time. Withdrawal or refusing to participate will not affect their relationship with The University of Texas at Austin (University) in anyway. You can agree to allow your child to be in the study now and change your mind later without any penalty.

What if my child does not want to participate?

In addition to your permission, your child must agree to participate in the study. If your child does not want to participate they will not be included in the study and there will be no penalty. If your child initially agrees to be in the study they can change their mind later without any penalty.

Will there be any compensation?

Neither you nor your child will receive any type of payment participating in this study.

How will your child's privacy and confidentiality be protected if s/he participates in this research study?

Your child's privacy and the confidentiality of his/her data will be protected. All research records will be locked in the principal investigator's office for the duration of the data collection and analysis. Only the principal investigator and one graduate assistant will have access to your data, and both have completed training in research with human participants. Your child's data may be used in publications and/or presentations but your child's identity will not be disclosed.

If your child participates in this study, he or she will be video recorded. Any video recordings will be store securely and only the research team will have access. Recordings and data will be kept for 2 years and then erased.

If it becomes necessary for the Institutional Review Board to review the study records, information that can be linked to your child will be protected to the extent permitted by law. Your child's research records will not be released without your consent unless required by law or a court order. The data resulting from your child's participation may be made available to other researchers in the future for research purposes not detailed within this consent form. In these cases, the data will contain no identifying information that could associate it with your child, or with your child's participation in any study.

Whom to contact with questions about the study?

Prior, during or after your participation you can contact the researcher, Robert A. Duke, at 512-471-0972 or send an email to bobduke@austin.utexas.edu for any questions or if you feel that you have been harmed. This study has been reviewed and approved by The University Institutional Review Board and the study number is 2014-06-0046.

Whom to contact with questions concerning your rights as a research participant?

For questions about your rights or any dissatisfaction with any part of this study, you can contact, anonymously if you wish, the Institutional Review Board by phone at (512) 471-8871 or email at orsc@uts.cc.utexas.edu.

IRB STUDY NUMBER: 2014-06-0046

Signature

You are making a decision about allowing your child to participate in this study. Your signature below indicates that you have read the information provided above and have decided to allow them to participate in the study. If you later decide that you wish to withdraw your permission for your child to participate in the study you may discontinue his or her participation at any time. You will be given a copy of this document.

NOTE: Include the following if recording is optional:

______ My child MAY be video recorded.

______ My child MAY NOT be video recorded.

____
Printed Name of Child

________________________________ ________________
Signature of Parent(s) or Legal Guardian Date

________________________________ ________________
Signature of Investigator Date

IRB USE ONLY
Study Number: 2014-06-0046
Approval Date: 08/05/2015
Expires: 08/04/2016

Assent for Participation in Research

Title: How did I do? Musicians' self-perceptions of performance during individual music practice.

Introduction

You have been asked to be in a research study about music learning. This study was explained to your parent and he/she/they said that you could be in it if you want to. We are doing this study to examine the relationship between listening and the execution of physical skill by looking at musicians' perceptions of their own playing.

What am I going to be asked to do?

If you agree to be in this study, you will be asked to

- Warm up for 2 minutes while you are being video recorded

- Practice a brief excerpt on your primary instrument for 5 minutes while you are being video recorded

- Review the audio portion of the video recording and identify moments when the outcome is different from what you intended by pressing a button on a computer keyboard.

-Answer four questions about your experience.

This study will take 20 minutes and there will be a total of 60 people in this study. Please note that you will be video recorded during this study. The IRB may audit study records at any time.

What are the risks involved in this study?

There are no foreseeable risks to participating in this study.

Do I have to participate?

No, participation is voluntary. You should only be in the study if you want to. You can even decide you want to be in the study now, and change your mind later. No one will be upset.

If you would like to participate you can sign this form. You will receive a copy of this form so if you want to you can look at it later.

Will I get anything to participate?

You will not receive any type of payment participating in this study, but the results will contribute to our understanding of human learning and musical skill development.

Who will know about my participation in this research study?

The records of this study will be kept private. Your responses may be used for a future study by these researchers or other researchers.

Whom to contact with questions about the study?

Prior, during or after your participation you can contact the researcher, Robert A. Duke, at 512-471-0972 or send an email to bobduke@austin.utexas.edu for any questions or if you feel that you have been harmed..

Signature

Modify the statement below depending on the age level:

Writing your name on this page means that the page was read by you and that you agree to be in the study. If you have any questions before, after or during the study, ask the person in charge. If you decide to quit the study, all you have to do is tell the person in charge.

______________________________ Signature of Participant

____________________ Date

Appendix B: Experiment 1—Instruction Script

Today you are being asked to participate in a study about music learning. You have been asked to bring a piece to practice that you have already begun working on but that you would not yet consider finished. In a moment, you will be video recorded while you complete a 2-minute warm-up followed by a 5-minute practice session on this piece. I will then ask you to review your recording and answer four questions. The study will take 20 minutes to complete, and you are welcome to discontinue your participation at any time before, during, or after your session today. Do you have any questions?

At this time, you can take up to two minutes to warm-up and acclimate yourself to the room in any way you wish. I will let you know once 2 minutes are over. [Pause for 2 minutes]

Please practice your piece or an excerpt of your piece as you would at home for the next five minutes. I will let you know once 5 minutes are over. [Record for 5 minutes]

Please listen to the recording of your practice session using these headphones. While you are listening, please press the "O" button on the computer keyboard every moment when the outcome from your instrument/voice is different from what you had intended. Once I start the recording, please continue reviewing your recording in this manner until you reach the end of your practice session. [Keypress Task]

Now I have a few questions to ask you. [Interview]

Appendix C: Experiment 1—Interview Questions

1. Do you feel like your button presses accurately marked the moments in your practice where there was a discrepancy between what you wanted to have happen and what actually happened?

2. Do you feel that all the moments you marked were things you noticed while you were practicing, or were some of them things you notice only on the playback?

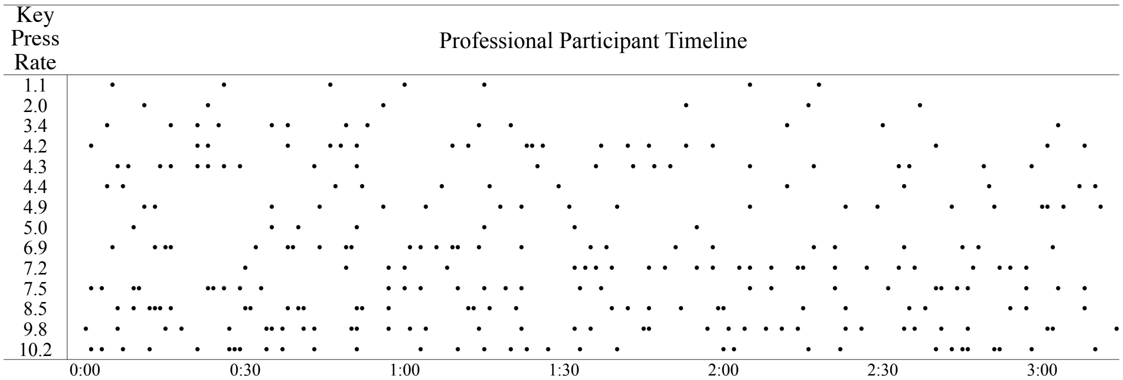
3. If yes, could you estimate the percentage of things you noticed on the playback?

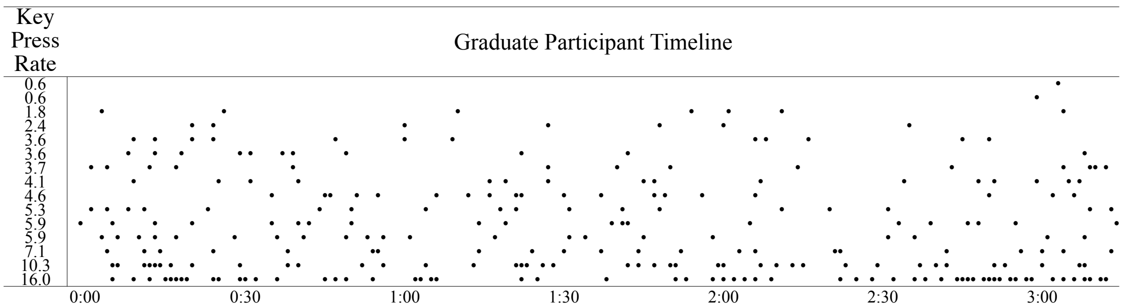
4. When there were differences, what was the nature of these differences? What were those differences caused by? (pitch, rhythm, phrasing, tone)

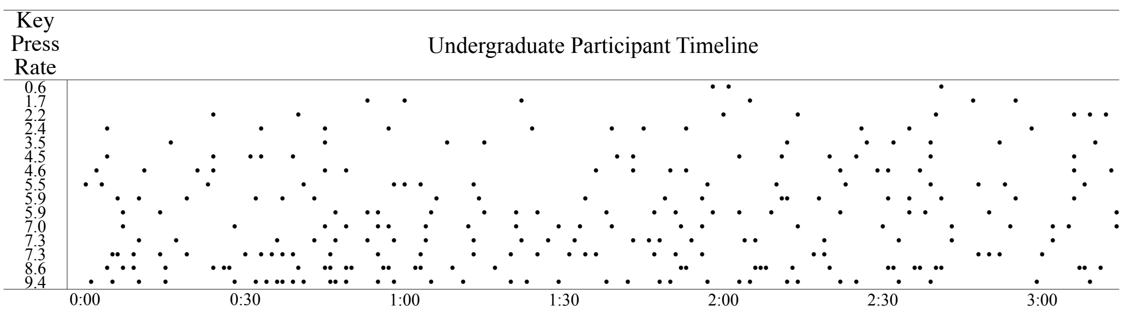
5. How long have you been working on this piece?

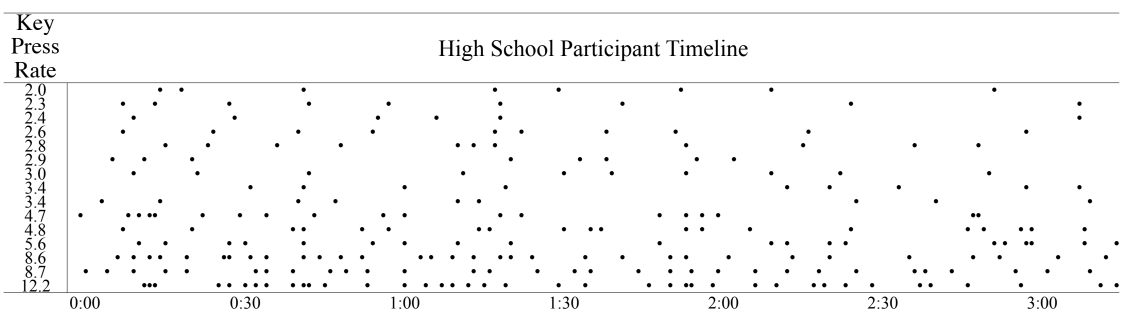
Appendix D: Experiment 1—Timeline of Perceived Discrepancies

Below is a timeline of participants' perceived discrepancies while listening to their own practice sessions. Each row in each figure represents the sequence of keypresses by a single participant. The rows are in order of increasing mean error rate. The x-axis in each figure indicates the duration of each recording. Each point represents a keypress (an indication that the participant perceived a discrepancy between what was intended and what was heard). Black bands indicate the end of each recording.





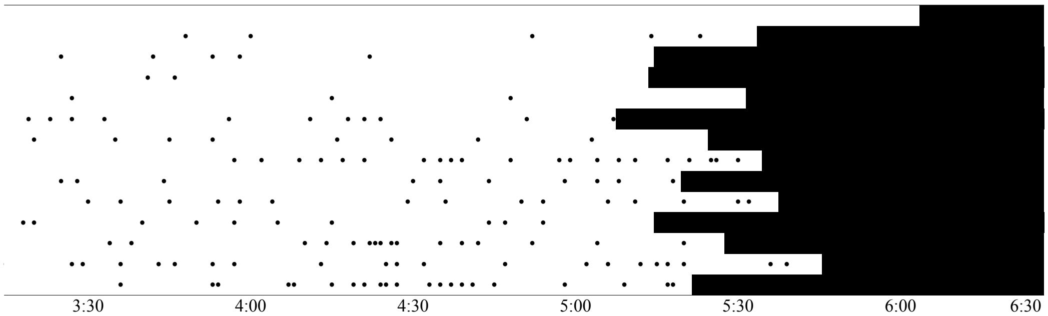




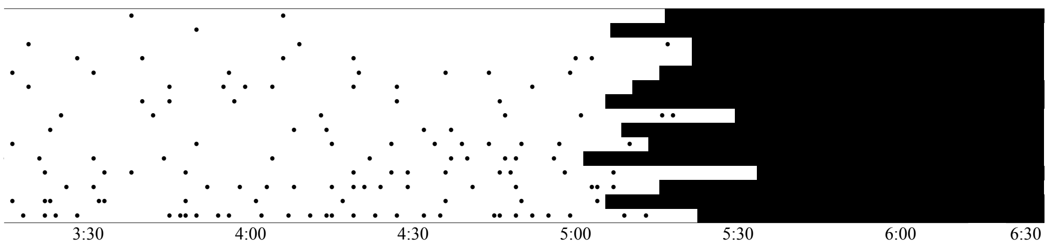
Timeline continues

Timeline, continued

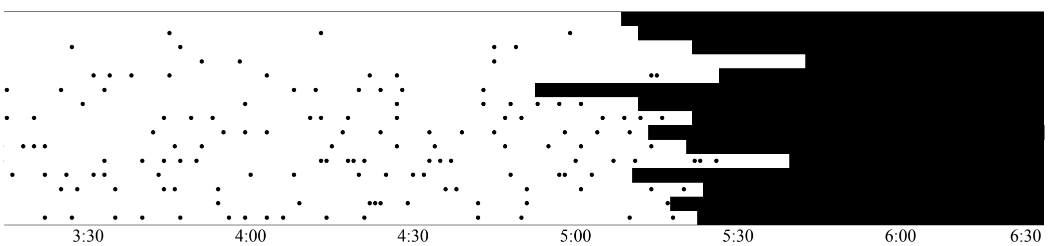
Professional Participant Timeline



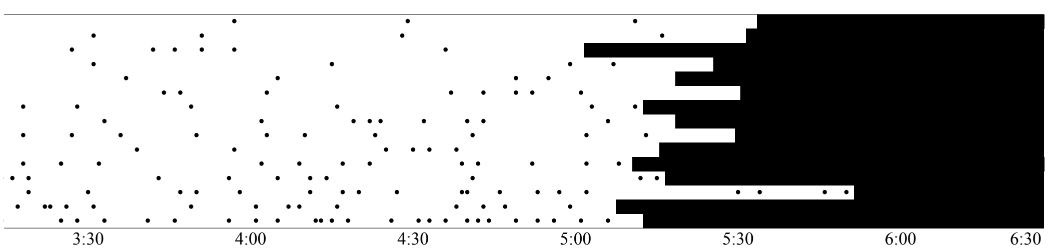
Graduate Participant Timeline



Undergraduate Participant Timeline



High School Participant Timeline



Appendix E: Experiment 2 and 3—Consent and Assent Forms

IRB USE ONLY
Study Number: 2016-06-0036
Approval Date: 06/21/2016
Expires: 06/20/2017

Consent Form for Participation in Research

Title
Perception of Discrepancies Between Intentions and Outcomes in Music Performance

Principal Investigator
Lani Hamilton
Assistant Instructor and Graduate Student, Music and Human Learning
Butler School of Music, The University of Texas at Austin

Faculty Investigator
Robert A. Duke, Ph.D.
Professor, Music and Human Learning
Butler School of Music, The University of Texas at Austin
512-471-0972, bobduke@austin.utexas.edu

Research purpose
You have been asked to participate in a research study about music learning. The purpose of this study is to examine the relationship between auditory discrimination and the execution of physical skill by assessing musicians' perceptions of several recordings. Please read the information below and feel free to ask questions before you decide if you would like to participate.

Experimental procedure
If you agree to participate, you will listen to brief recordings of musicians practicing. While you listen, you will press a button on the computer keyboard any moment when what you hear is different from what you would intend if this were a recording of you practicing right now. Afterward, you will be asked several short questions. The study will take 30 minutes to complete and there will be a total of 60 participants in the study.

Benefits
You will not receive any direct benefit from participating in this study; but the results will contribute to our understanding of human learning and musical skill development.

Risks
The risks associated with this study are no greater than everyday life.

Compensation

You will not receive any compensation for your participation.

Participation

Your participation is voluntary, and you may withdraw from this study at any time. You may also refrain from answering any question asked of you for any reason. These choices can be made without penalty or loss of benefits to which you are otherwise entitled and without jeopardizing your standing with the University of Texas at Austin.

Data confidentiality

All research data is confidential and will not be linked to your identity. All research records will be locked in the principal investigator's office for the duration of the data collection and analysis. Only the principal investigator (Lani Hamilton) and one faculty investigator (Robert Duke) will have access to your data, and both have completed training in research with human participants. Your data may be used in publications and/or presentations but your identity will not be disclosed.

If it becomes necessary for the Institutional Review Board to review the study records, information that can be linked to you will be protected to the extent permitted by law. Your research records will not be released without your consent unless required by law or court order. The data resulting from your participation may be made available to other researchers in the future for research purposes not detailed within this consent form. In these cases, the data will contain no identifying information that could associate it with you, or with your participation in any study.

Questions

If you have questions prior to, during, or after participating in this study, please contact the primary investigator using the contact information listed at the top of this form. For questions about your rights or any dissatisfaction with any part of this study, you can contact, anonymously if you wish, the Institutional Review Board by phone at (512) 471-8871 or email at orsc@uts.cc.utexas.edu.

Results

If you would like to receive the results of this study, please indicate your email address or other contact information below.

Perception of Discrepancies Between Intentions and Outcomes in Music Performance

Signature
You are welcome to ask questions before or after signing this form; and by singing it, you are not waiving any of your legal rights. You are able to withdraw from the study at any time without penalty.

________________________________ ___________________________
Signature of Participant Date

____
Printed Name of Participant

____
(optional) Email Address for Results

________________________________ ___________________________
Signature of Investigator Date

IRB USE ONLY
Study Number: 2016-06-0036
Approval Date: 06/21/2016
Expires: 06/20/2017

Parental Permission for Children Participation in Research

Title

Perception of Discrepancies Between Intentions and Outcomes in Music Performance

Introduction

The purpose of this form is to provide you (as the parent of a prospective research study participant) information that may affect your decision as to whether or not to let your child participate in this research study. The person performing the research will describe the study to you and answer all your questions. Read the information below and ask any questions you might have before deciding whether or not to give your permission for your child to take part. If you decide to let your child be involved in this study, this form will be used to record your permission.

Purpose of the Study

If you agree, your child will be asked to participate in a research study about music learning. The purpose of this study is to examine the relationship between auditory discrimination and the execution of physical skill by accessing musicians' perceptions of several recordings.

What is my child going to be asked to do?

If you allow your child to participate in this study, she or he will

- Listen to recordings of musicians practicing
- Press a button on a computer keyboard every moment when what she/he hears is different from what she/he would intend if practicing right now
- Answer questions about her or his experience

This study will take 30 minutes to complete and there will be a total of 60 people in this study.

What are the risks involved in this study?

The risks associated with this study are no greater than everyday life.

What are the possible benefits of this study?

Your child will not receive any direct benefit from participating in this study; but the results will contribute to our understanding of human learning and musical skill development.

Does my child have to participate?

No, your child's participation in this study is voluntary. Your child may decline to participate or to withdraw from participation at any time. Withdrawal or refusing to participate will not affect their relationship with The University of Texas at Austin in anyway. You can agree to allow your child to be in the study now and change your mind later without any penalty.

What if my child does not want to participate?

In addition to your permission, your child must agree to participate in the study. If your child does not want to participate they will not be included in the study and there will be no penalty. If your child initially agrees to be in the study they can change their mind later without any penalty.

Will there be any compensation?

Neither you nor your child will receive any type of payment for participating in this study.

How will your child's privacy and confidentiality be protected if s/he participates in this research study?

Your child's privacy and the confidentiality of his/her data will be protected. All research records will be locked in the principal investigator's office for the duration of the data collection and analysis. Only the principal investigator (Lani Hamilton) and one faculty investigator (Robert Duke) will have access to your data, and both have completed training in research with human participants. Your child's data may be used in publications and/or presentations but your child's identity will not be disclosed.

Data on your child's button presses will be recorded on a computer. The data will be kept for 2 years and then erased.

If it becomes necessary for the Institutional Review Board to review the study records, information that can be linked to your child will be protected to the extent permitted by law. Your child's research records will not be released without your consent unless required by law or a court order. The data resulting from your child's participation may be made available to other researchers in the future for research purposes not detailed within this consent form. In these cases, the data will contain no identifying information that could associate it with your child, or with your child's participation in the study.

Whom to contact with questions about the study?

Prior, during or after your child's participation you can contact the researcher, Robert A. Duke, at 512-471-0972 or send an email to bobduke@austin.utexas.edu for any questions. For questions about your rights or any dissatisfaction with any part of this study, you can contact, anonymously if you wish, the Institutional Review Board by phone at (512) 471-8871 or email at orsc@uts.cc.utexas.edu.

Results

If you would like to receive the results of this study, please indicate your email address or other contact information below.

Perception of Discrepancies Between Intentions and Outcomes in Music Performance

Signature

You are making a decision about allowing your child to participate in this study. Your signature below indicates that you have read the information provided above and have decided to allow them to participate in the study. If you later decide that you wish to withdraw your permission for your child to participate in the study you may discontinue his or her participation at any time. You will be given a copy of this document.

______________________________ ______________________________

Printed Name of Child | Printed Name of Parent(s)/Legal Guardian

______________________________ _______________

Signature of Parent(s)/Legal Guardian | Date

____

(optional) Email Address for Results

______________________________ _______________

Signature of Investigator | Date

IRB USE ONLY
Study Number: 2016-06-0036
Approval Date: 06/21/2016
Expires: 06/20/2017

Assent for Participation in Research

Title

Perception of Discrepancies Between Intentions and Outcomes in Music Performance

Introduction

You have been asked to be in a research study about music learning. This study was explained to your parent and he/she/they said that you could be in it if you want to. We are doing this study to examine the relationship between listening and the execution of physical skill by looking at musicians' perceptions of several recordings.

What am I going to be asked to do?

If you agree to be in this study, you will be asked to

- Listen to recordings of musicians practicing

- Press a button on a computer keyboard any moment when what you hear is different from what you would intend if this were a recording of you practicing right now

- Answer questions about your experience

This study will take 30 minutes to complete and there will be a total of 60 people in this study.

What are the risks involved in this study?

The risks associated with this study are no greater than everyday life.

Do I have to participate?

No, participation is voluntary. You should only be in the study if you want to. You can even decide you want to be in the study now, and change your mind later. No one will be upset.

If you would like to participate you can sign this form. You will receive a copy of this form so if you want to you can look at it later.

Will I get anything to participate?

You will not receive any type of payment participating in this study, but the results will contribute to our understanding of human learning and musical skill development.

Who will know about my participation in this research study?

The records of this study will be kept private. Your responses may be used for a future study by these researchers or other researchers. The IRB may audit study records at any time.

Whom to contact with questions about the study?

Prior, during or after your participation you can contact the researcher, Robert A. Duke, at 512-471-0972 or send an email to bobduke@austin.utexas.edu for any questions. For questions about your rights or any dissatisfaction with any part of this study, you can contact, anonymously if you wish, the Institutional Review Board by phone at (512) 471-8871 or email at orsc@uts.cc.utexas.edu.

Perception of Discrepancies Between Intentions and Outcomes in Music Performance

Signature
Writing your name on this page means that you agree to be in the study. If you have any questions before, after or during the study, ask the person in charge. If you decide to quit the study, all you have to do is tell the person in charge.

________________________________ ________________
Signature Date

____
Printed Name

____
(optional) Email Address for Results

________________________________ ________________
Signature of Investigator Date

Appendix F: Experiment 2—Instruction Script

In a moment, you will listen to a recording that you made 1-2 years ago. You may recall that shortly after you made this recording, you listened to it and pressed a computer key each time you heard a discrepancy between what you had intended and what you played on the recording.

Even though you recorded this session a long time ago, we'd like you to do the same task again. Imagine that you had just recorded this practice session now. Please press the letter "O" every time you hear something that deviates from what you would want if this were a recording of you practicing right now. For example, you may hear a phrase ending where the last note doesn't end beautifully or a passage during which the style of articulation is inconsistent or notes that are out of tune.

The recording will begin in just a moment. Please let the proctor know if you have any questions before you begin.

Appendix G: Experiment 2—Interview Questions

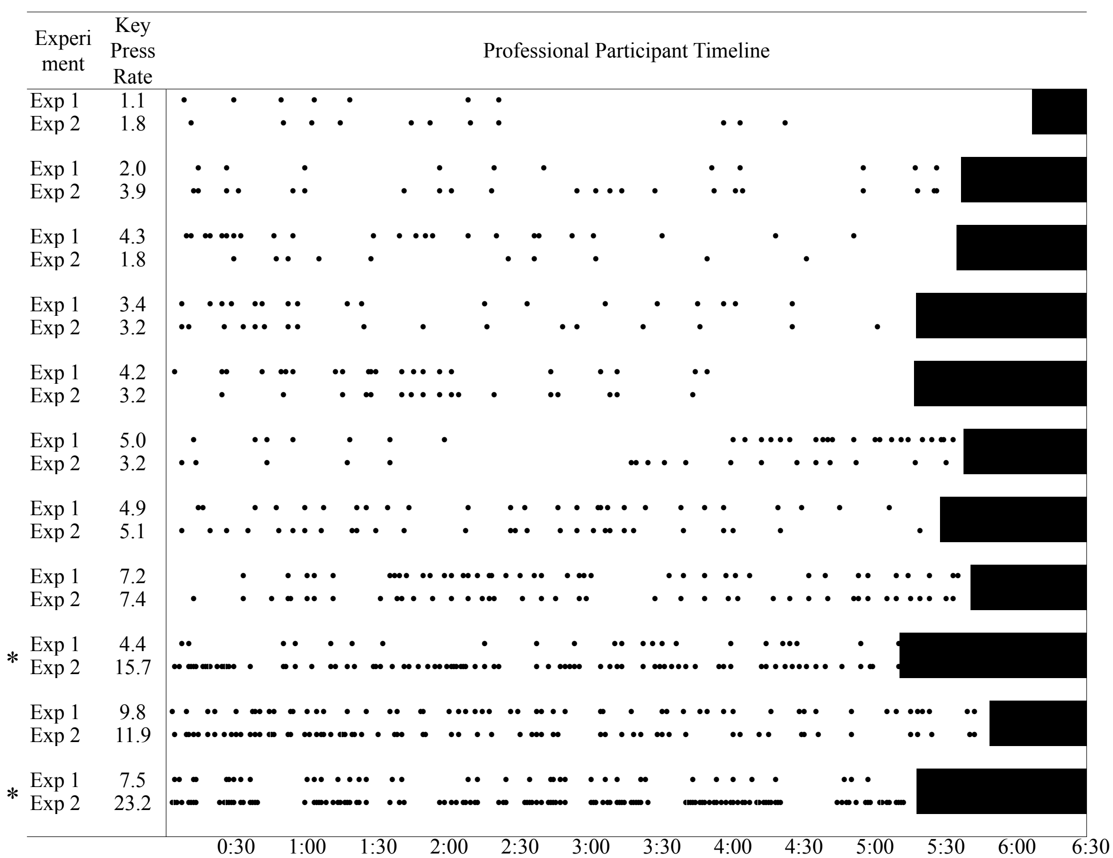
1. Do you feel like your button presses accurately reflect what you perceived?

2. What types of discrepancies did you hear that led you to push the button? What types of errors did you hear?

3. Is there anything else about this experience that you would like us to know?

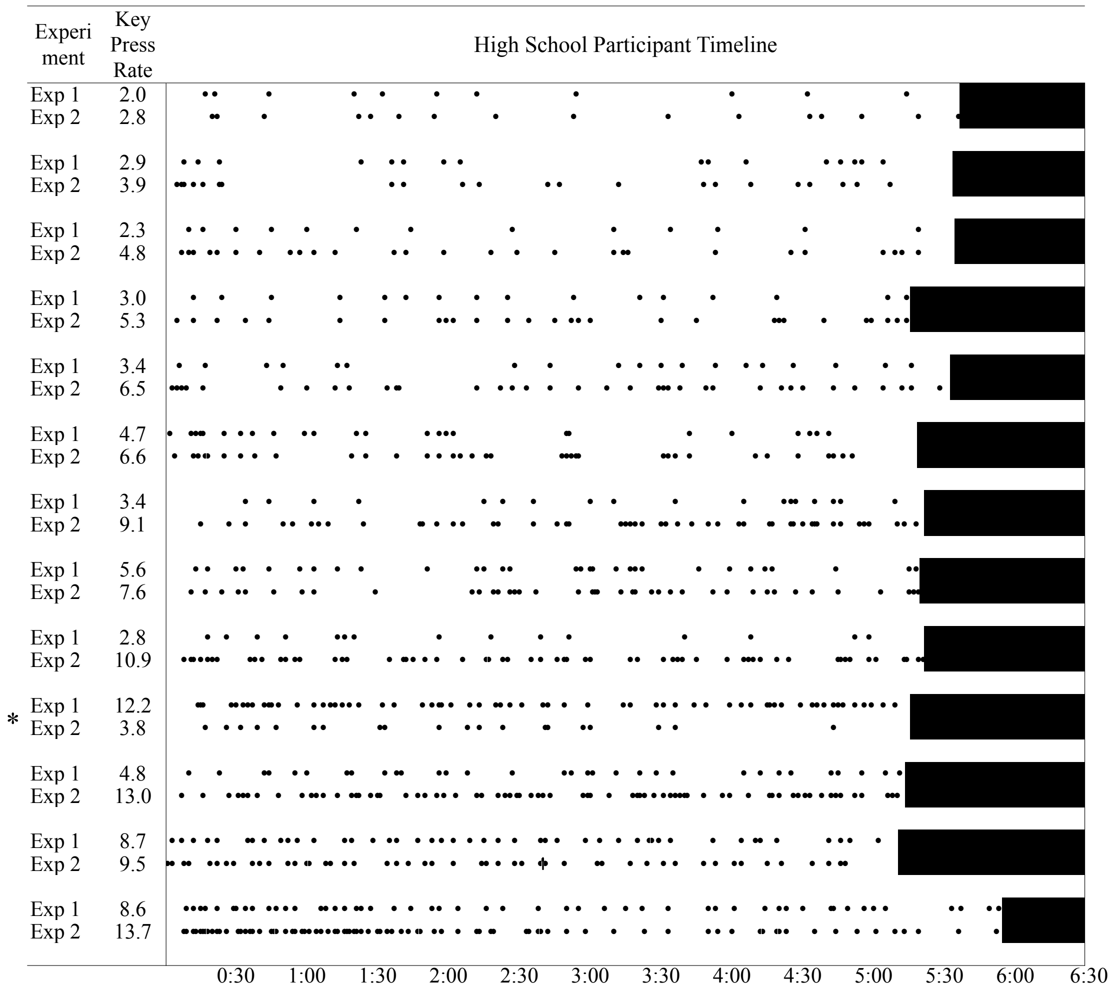
Appendix H: Experiment 2— Timeline of Perceived Discrepancies

Below is a timeline of participants' key presses while listening to their own practice session at two different points in time. Each row pair represents the sequence of keypresses by each participant. The top row of each pair represents participants' keypresses taken immediately after making the recording (during Experiment 1), and the bottom row of each pair represents participants' keypresses taken approximately 2 years later (during Experiment 2). The rows are in order of decreasing mean rates of keypresses. Outliers marked with asterisks. Black bands indicate the end of each recording.



Timeline continues

Timeline, continued



Appendix I: Experiment 3—Instruction Script

In a moment, you will listen to four excerpts of different violinists practicing. Each excerpt is approximately 2 minutes long. You may not know the pieces these individuals are working on and they may be playing an instrument that is different from your own. We realize that you cannot possibly know what the performers are thinking. But, we'd like you to imagine that these are recordings of yourself practicing.

While you are listening, please press the letter "O" every time you hear something that deviates from what you would want if this were a recording of you practicing right now. For example, you may hear a phrase ending where the last note doesn't end beautifully or a passage during which the style of articulation is inconsistent or notes that are out of tune.

To get a sense of how this will feel, you can practice the task right now. You will hear a short 20 second excerpt of a violinists playing. While you are listening, please press the letter "O" every time you hear something that deviates from what you would want if this were a recording of you practicing right now. This is just practice, but go ahead and press the letter "O" as you listen. Please let the proctor know if you have any questions. [Practice Recording]

Now that you have practiced, you will begin the task. You will be listening to four excerpts of different violinists practicing. Each excerpt is approximately 2 minutes long. While you are listening, please press the letter "O" every time you hear something that deviates from what you would want if this were a recording of you practicing right now.

Please let the proctor know if you have any questions before you begin.

Appendix J: Experiment 3—Interview Questions

1. Do you feel like your button presses accurately reflect what you perceived?

2. What types of discrepancies did you hear that led you to push the button? What types of errors did you hear?

3. How familiar to you is this piece?

Never heard it 1 2 3 4 5 Performed it in public

4. In your opinion, is this piece well suited to the performer's skill level?

Not well suited at all 1 2 3 4 5 Very well suited

5. In your opinion, should a string teacher assign this individual this piece?

__________ No

__________ Yes

6. What do you think is the experience level of this musician?

__________ High School

__________ Undergraduate music major

__________ Graduate performance major

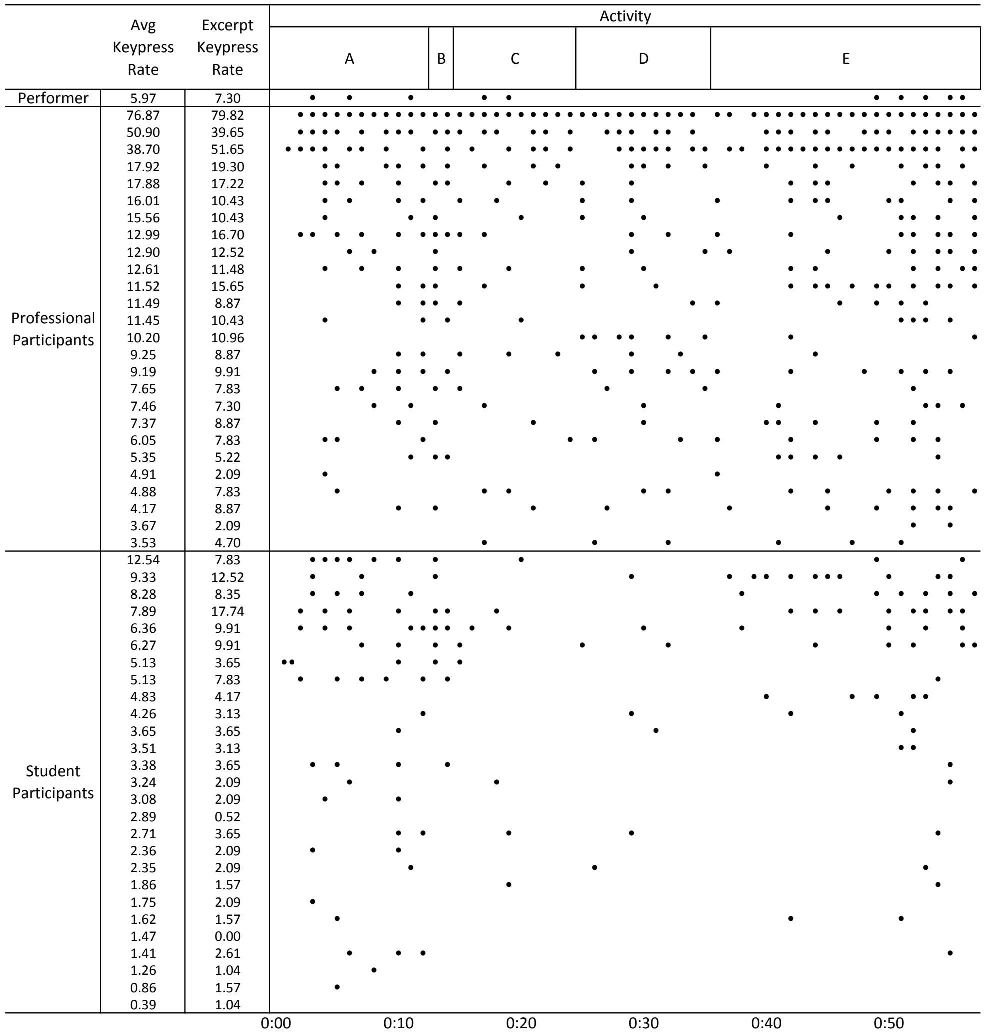
__________ Professional

Appendix K: Experiment 3— Timeline of Perceived Discrepancies

During the practice excerpt, Student 1 progresses through the following activities:

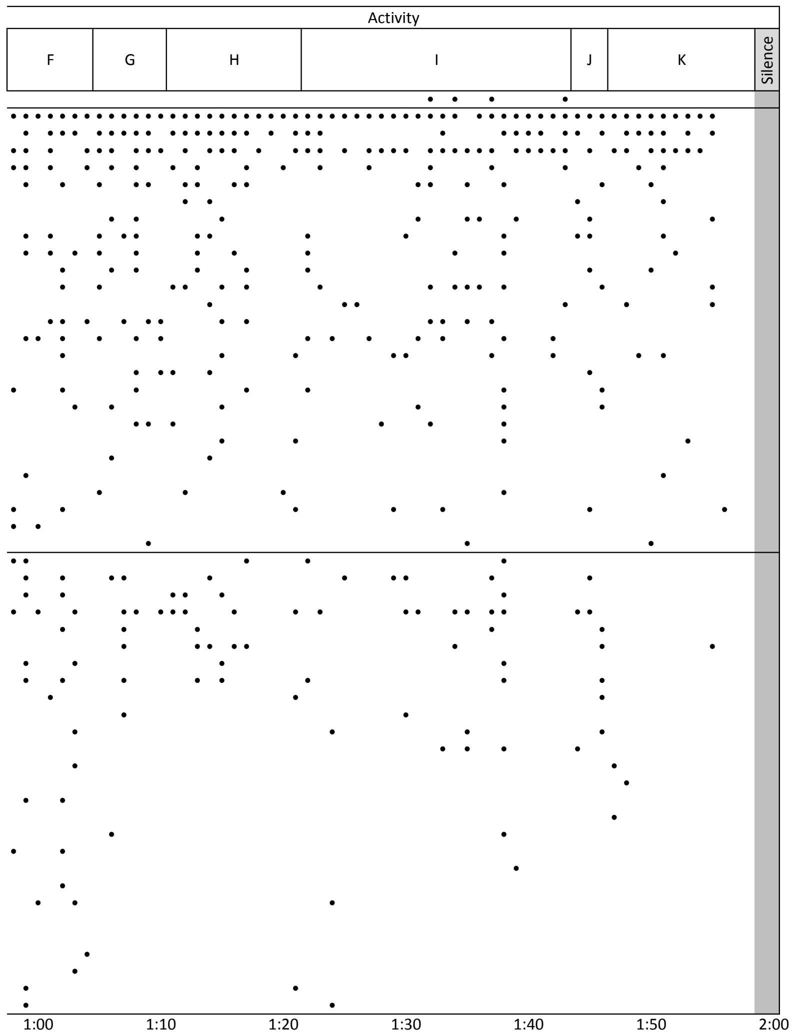
A. Plays the beginning of a short passage until the first shift, repeating 4 times
B. Plays just the shift
C. Plays through the entire passage
D. Plays through entire passage again
E. Puts passage into context, stopping abruptly for out of tune note
F. Isolates section with out of tune note, plays through 2 times
G. Plays isolated section again, this time continuing towards the end of the passage but stopping abruptly for out of tune note
H. Repeats section, continuing towards the end of the passage, stopping abruptly
I. Plays through entire passage, slightly faster, stopping abruptly at very end for out of tune note
J. Isolates section with out of tune note, checking octave intervals
K. Plays through end of passage

Below is a timeline of participants' perceived discrepancies while listening to Student 1. The x-axis in each figure indicates the duration of each recording. Each row in each figure represents the sequence of keypresses by a single participant, and each point represents a keypresses (an indication that the participant perceived a discrepancy between what they had intended and what they heard). The rows are presented in order from the participant with the highest mean rate of keypresses for all four excerpts at the top to the participant with the lowest rate of keypresses at the bottom.



Timeline continues

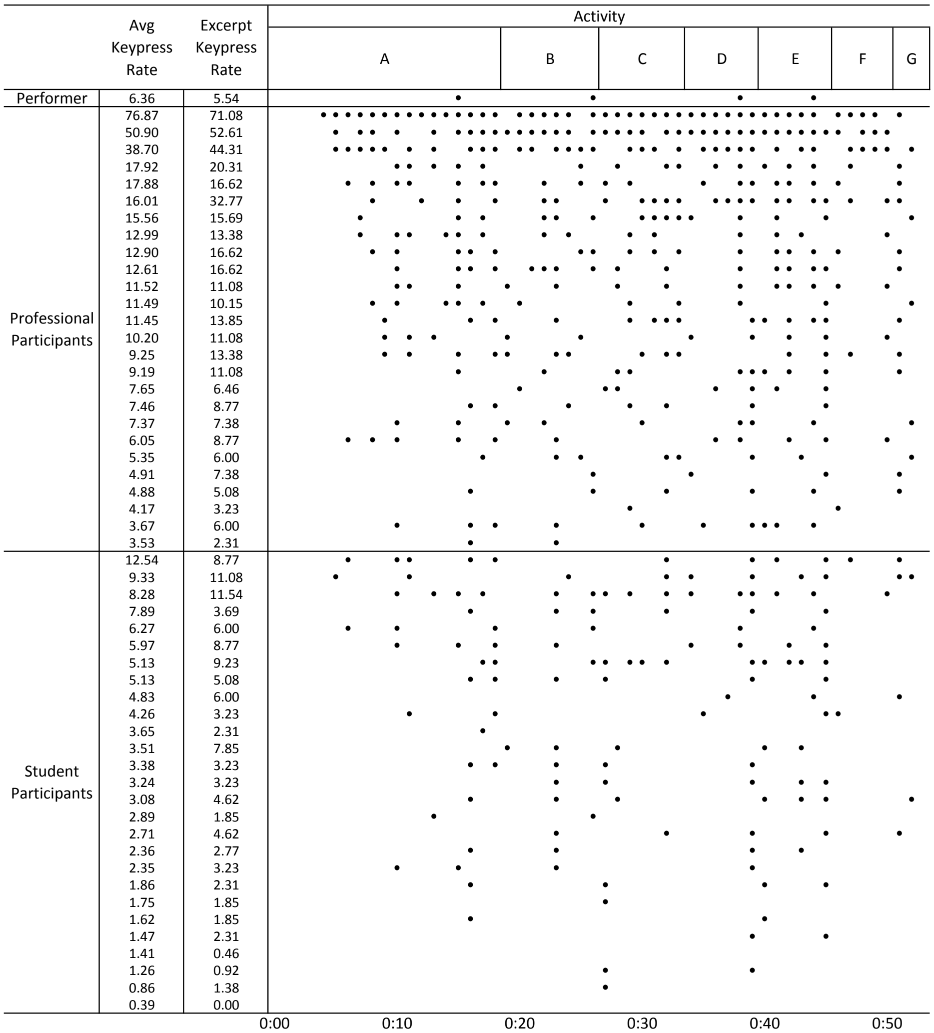
Timeline, continued



During the practice excerpt, Student 2 progresses through the following activities:

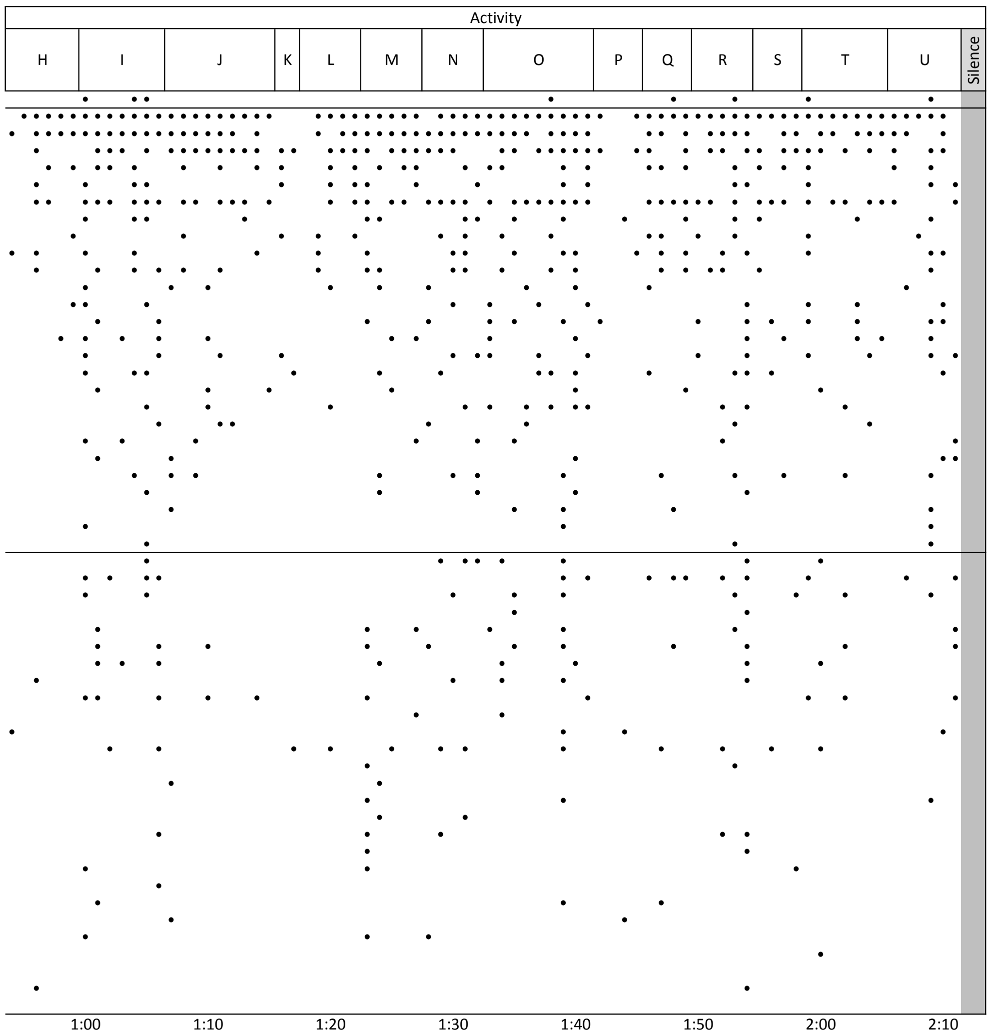
A. Plays through passage with metronome set at quarter note = 80 bpm. Repeats one note that is out of tune towards the end of the passage
B. Plays shorter section that contains the out of tune note
C. Plays shorter section at half tempo, now *eighth note* = 80 bpm
D. Plays shorter section, same tempo
E. Plays shorter section, same tempo
F. Plays shorter section, same tempo
G. Increases metronome speed, now eight note = 90 bpm
H. Plays shorter section at faster tempo
I. Plays shorter section, same tempo
J. Puts shorter section in context, same tempo
K. Increases metronome speed, now eighth note = 100 bmp
L. Plays shorter section at faster tempo
M. Plays shorter section, same tempo
N. Plays shorter section, same tempo
O. Puts shorter section in context, same tempo
P. Increases metronome speed, now eighth note = 110 bpm
Q. Plays shorter section at faster tempo
R. Plays shorter section again, same tempo
S. Plays shorter section again, same tempo
T. Puts shorter section in context, same tempo
U. Plays section in context at double tempo, now *quarter note* = 110 bmp

Below is a timeline of participants' perceived discrepancies while listening to Student 2. The x-axis in each figure indicates the duration of each recording. Each row in each figure represents the sequence of keypresses by a single participant, and each point represents a keypresses (an indication that the participant perceived a discrepancy between what they had intended and what they heard). The rows are presented in order from the participant with the highest mean rate of keypresses for all four excerpts at the top to the participant with the lowest rate of keypresses at the bottom.



Timeline continues

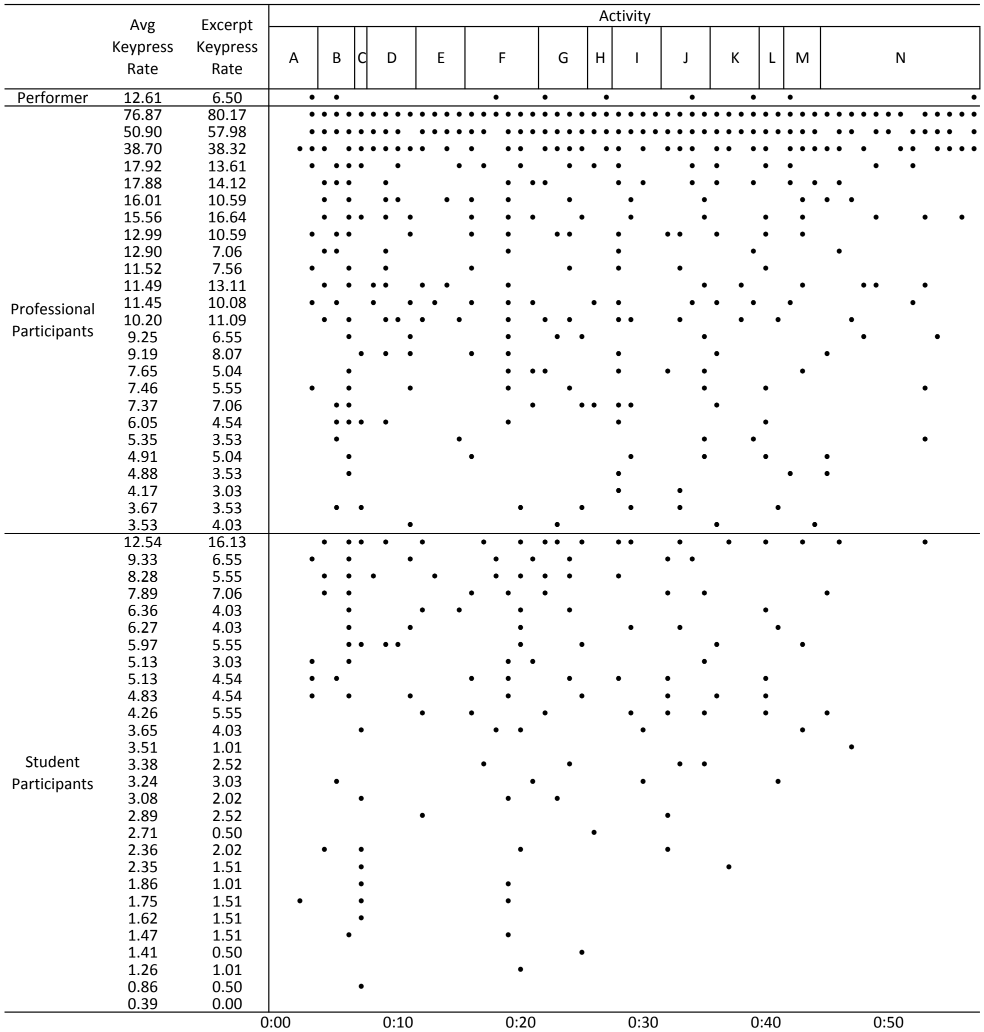
Timeline, continued



During the practice excerpt, Expert 1 progresses through the following activities:

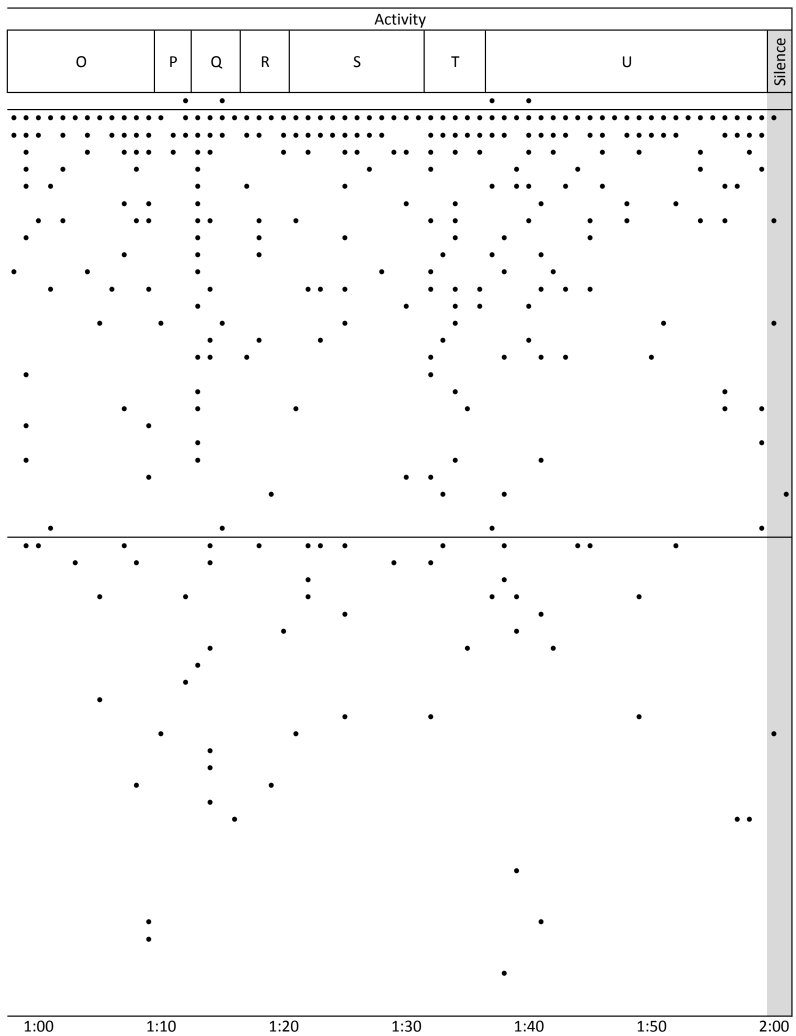
A. Practices first two notes of short passage out of time with a pivot fingering
B. Begins short passage with a different fingering (descending shift), abrupt stop after out of tune note
C. Plays first two notes of short passage with a different fingering (ascending shift)
D. Plays short passage in time with ascending shift fingering
E. Plays short passage in time with ascending shifting fingering again
F. Plays short passage slightly slower with pivot fingering, correcting the intonation of one pitch
G. Plays short passage at slower tempo with pivot fingering, again correcting the intonation of the same pitch
H. Plays first two notes of short passage with pivot fingering, abruptly stopping after same pitch is out of tune
I. Begins short passage at slower tempo with descending shift fingering
J. Plays short passage with descending shift in tempo
K. Plays short passage in tempo with bigger crescendo and a slurred bowing
L. Plays first two notes of short passage with ascending shift fingering
M. Plays short passage in tempo with ascending shift fingering, less crescendo and different part of the bow
N. Plays through longer passage in tempo with descending shift fingering and a large inflection
O. Plays through longer passage in tempo with ascending shift fingering and less inflection
P. Plays shorter passage with descending shift fingering; abruptly stops after pitch is out of tune
Q. Plays shorter passage with descending shift fingering
R. Plays shorter passage with ascending shift fingering
S. Plays longer passage in tempo with ascending shift fingering with different bowing style (lighter, less sustained sound, upper half of bow instead of frog)
T. Plays shorter excerpt with descending shift fingering. Uses more sustained, heavy sound
U. Plays longer passage with descending shift fingering

Below is a timeline of participants' perceived discrepancies while listening to Expert 1. The x-axis in each figure indicates the duration of each recording. Each row in each figure represents the sequence of keypresses by a single participant, and each point represents a keypresses (an indication that the participant perceived a discrepancy between what they had intended and what they heard). The rows are presented in order from the participant with the highest mean rate of keypresses for all four excerpts at the top to the participant with the lowest rate of keypresses at the bottom.



Timeline continues

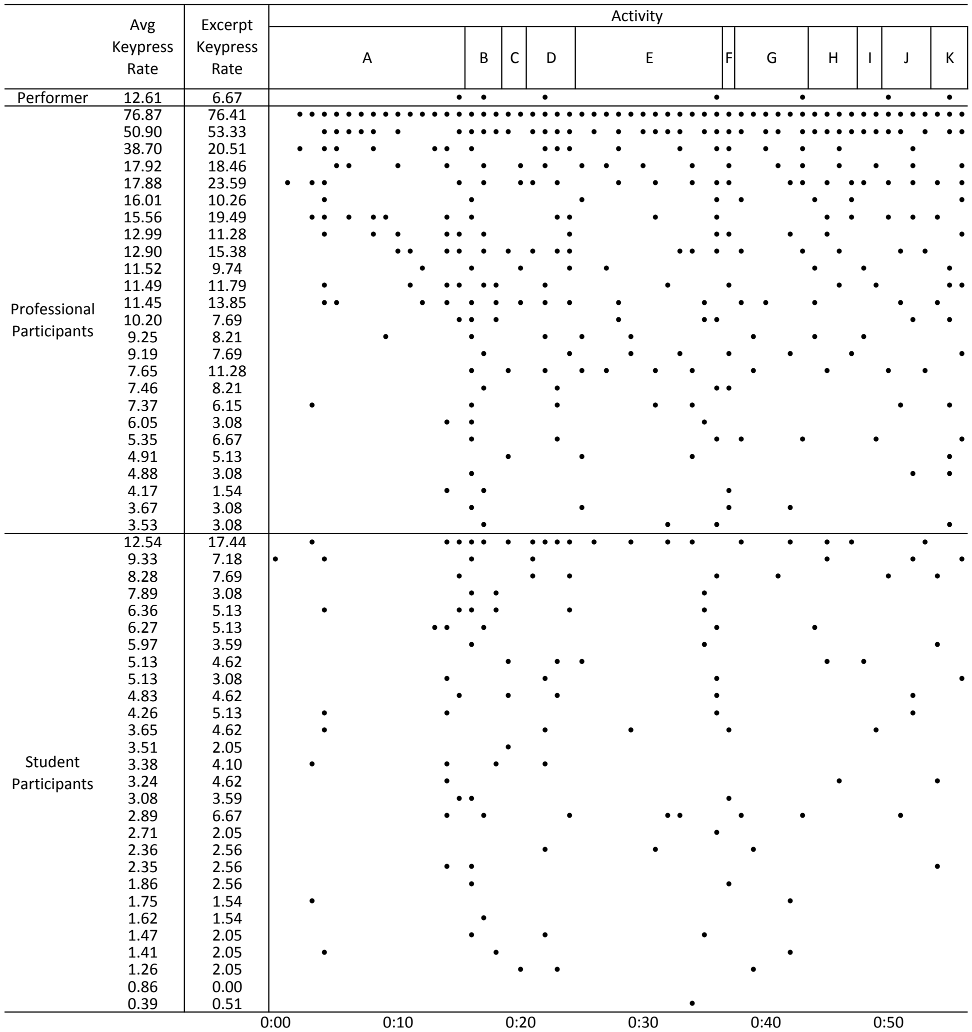
Timeline, continued



During the practice excerpt, Expert 2 progresses through the following activities:

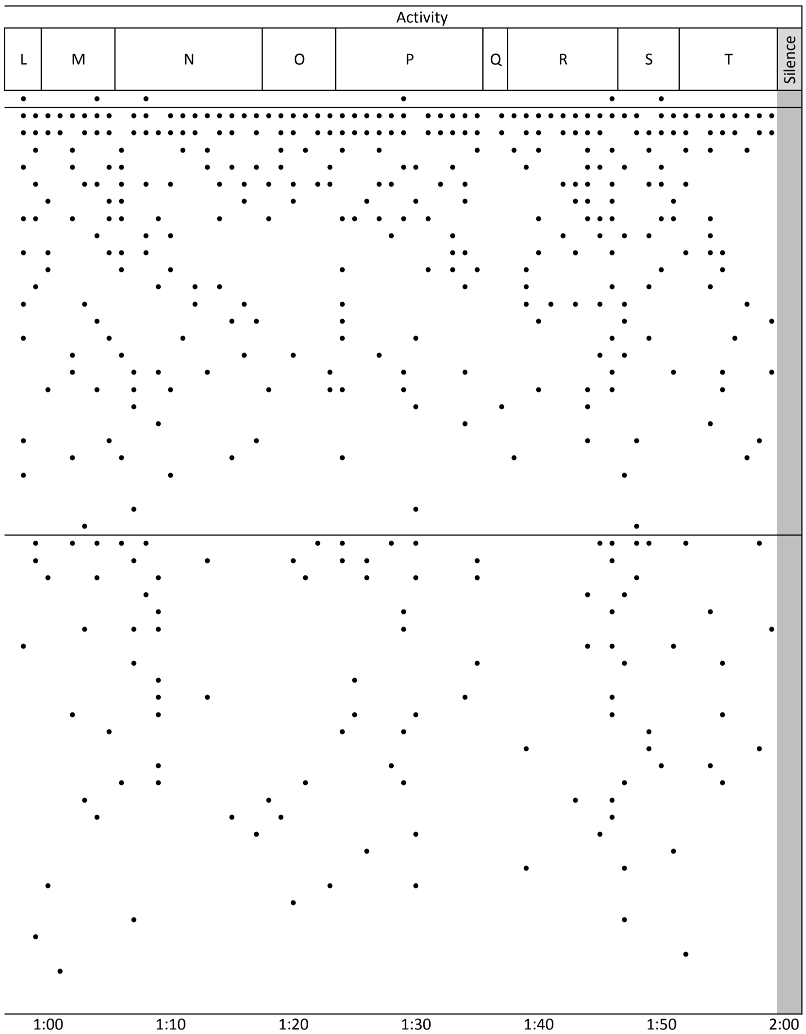
A. Plays through long passage
B. Goes back to out of tune note, playing the surrounding notes slowly and checking with open string
C. Puts passage back into context, playing in tempo. Stops abruptly for out of tune note
D. Plays shifting passage slowly, repeating a few out of tune notes
E. Plays shifting passage again even more slowly, repeating several notes that are out of tune. Frequently checks intonation with open strings
F. Plays shifting passage, focusing on one out of tune note
G. Plays shifting passage again slower
H. Plays first half of shifting passage, repeating out of tune notes
I. Plays first half of shifting passage fast, stopping abruptly again for out of tune note
J. Plays all of shifting passage in tempo, stopping abruptly for out of tune note in second half
K. Plays second half of shifting passage
L. Plays all of shifting passage, taking time between the first half and the second half for shift
M. Checks intonation of intervals at the end of shifting passage
N. Slowly practice second half of shifting passage, frequently repeating and correcting out of tune notes
O Plays to the end of the passage slowly
P. Repeats end of the passage slowly, frequently repeating and correcting out of tune notes
Q. Begins shifting passage in faster tempo, abruptly stops for out of tune note
R. Plays entire shifting passage
S. Repeats the end of the passage more slowly, frequently repeating and correcting out of tune notes
T. Plays the end of the passage in fast tempo

Below is a timeline of participants' perceived discrepancies while listening to Expert 2. The x-axis in each figure indicates the duration of each recording. Each row in each figure represents the sequence of keypresses by a single participant, and each point represents a keypresses (an indication that the participant perceived a discrepancy between what they had intended and what they heard). The rows are presented in order from the participant with the highest mean rate of keypresses for all four excerpts at the top to the participant with the lowest rate of keypresses at the bottom.



Timeline continues

Timeline, continued



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