Palmer, C., & Smykovskyi, A. (2025). Memory constraints in motor sequences: Typing and music performance. In press, *American Journal of Psychology*.

Memory Constraints in Motor Sequences:

Typing and Music Performance

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In Press, *American Journal of Psychology*

Special Issue: Festschrift for Gordon Logan

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Abstract

Humans across cultures exhibit incredibly flexible and fast typing on computer keyboards, cell phones, and other input devices, often at rates faster than the content can be spoken. Many individuals in Western cultures can play a musical instrument, also at faster rates than the same content can be sung. These flexible and fluent tasks exhibit several similarities in the role of instance-based memory and motor experiences, especially for comparisons that are text-based (typing or performing from notation). We consider the contributions of Gordon Logan's hierarchical organization of memory processes as applied to typing, compared with theoretical developments in music performance. Based on Logan's contributions, we identify similarities and differences in the goal-directed behaviors of typing and music, including: schemas in motor learning, with an emphasis on eye-hand coordination metrics observed in typing and music; serial ordering processes in action sequences, with consideration of similarity-based constraints on the types of errors observed; and speed-accuracy tradeoffs identified in both domains. Despite the fact that typing is a speeded task with a goal to produce events as quickly as possible, whereas music performance is a rhythmic task with a goal to produce events at a specific time, both tasks exhibit important shared constraints of instance-based memory and motor learning. We end with a discussion of Logan's work and its application to future research in music cognition.

Introduction

Gordon Logan's contributions are widely known for a mathematically grounded approach to understanding cognitive control in goal-directed behaviors. Equally important are his contributions to models of attention, automaticity, serial order and speed-accuracy tradeoffs in action sequences like typing and music. Much of Logan’s work, first highlighted in the Instance Theory of Automatization (1988), addresses the acquisition of skills that rely on automatized processes as novices gain knowledge in the form of instances of memories. Logan's experiments often focused on the domain of skilled typing, but he commented on similar cognitive constraints that arise in other domains such as music, another behavior characterized by demands to produce long sequences quickly and flexibly. Logan's love of music (and blues in particular) was evident in several arenas; he once gave a talk at the University of Illinois during which he performed the "Instance Theory Blues" on his Fender Stratocaster guitar (personal communication, G.S. Dell, December 18, 2024).

Logan and colleagues' discoveries in attention, automaticity and cognitive control applied to typing skills offer interesting similarities and differences with cognitive constraints in music performance skills. In particular, the instance-based memory and motor learning experiences share similarities with the role of variability in music tasks, specifically in motor learning. In the next sections we identify similarities and differences in theoretical developments that address the goal-directed behaviors of typing and music, including: schemas in motor learning; serial order in action sequences; and speed-accuracy tradeoffs in skilled action (see Table 1 for a summary of proposed similarities and differences). We conclude with a discussion of Logan’s work and its application to future research in music cognition.

A. Motor learning

Logan's Instance Theory (Logan, 1988; 2002) reveals parallels with influential theories of motor learning that have also influenced the theoretical development of music performance. Instance Theory offers a broad framework for skill acquisition that incorporates motor learning as well as memory constraints; it is applied to explain the acquisition of motor skills such as touch typing or typing from written text. Logan's instance-based theory does not predict general procedural learning as some motor theories do; ts motor learning components for (sequential) typing can be compared to complex tasks like music performance. We briefly review Logan's parallels with two motor learning theories that have influenced music performance: Schmidt's (1975) motor schemas and Adam's (1971) closed loop theory, and their applications to music.

Schmidt's Schema Theory

Instance theory draws a parallel with Schmidt's (1975) seminal Schema Theory of discrete motor skills. Whereas Logan (2002) views learning as the accumulation of specific instances in memory: distinct representations of each encounter with a context that enables more efficient retrieval, Schmidt (1975) emphasizes the development of generalized motor programs: schemas that are built up though practice, such as what happens during constant or varied practice. Furthermore, recall schemas guide movement production and recognition schemas assess response accuracy. Variability in practice is effective under random conditions as reconstruction of motor programs makes schemas more adaptable to different contexts (Lee, Magill, & Weeks, 1985). Thus, variable practice not only builds a diverse set of instance-based contexts, as in Logan's Instance Theory, but also reinforces adaptable motor schemas, as proposed in Schmidt's Schema Theory (Schmidt, Lee, Winstein, Wulf & Zelaznik, 2019), improving the ability to apply acquired motor skills flexibly across various situations, including music performance.

A challenge for understanding music learning and performance is how individuals learn the optimal motor patterns and identify the best practice conditions for them. Whereas most people type competently enough to produce any sentence after a few years, musicians commonly practice on their instrument for 8-10 years or more (cf. Gladwell's 10,000 hours rule) before they reach askill level that permits them to perform complex musical pieces. Does variability in practice influence its effectiveness in enhancing music performance? Pacey's (1993) study of beginner child violinists investigated the effects of variable practice at different observation points that occurred over a three-week period. The study introduced variable practice (defined as bowing and fingering techniques to alter loudness, tempo, and pitch) at different observation points to distinguish whether improvement over time resulted from the variable practice itself or from other factors, such as natural learning effects from beginning to end of practice. Regardless of when the varied practice began relative to the first or last practice session, it consistently improved loudness and tempo control across all groups (Pacey, 1993). Other findings also support that variable practice in novice pianists' positions of hand movements for melodic leaps, based on different spatial (interval) sizes, showed greater improvement than fixed (constant) practice that repeated the same spatial leap, based on measures of performance speed and confidence (Bangert, Wiedemann, & Jabusch, 2014). Even novices with no music performance experience show enhanced motor learning with varied practice; Caramiaux and colleagues (2018) learned novel finger sequences on a piano keyboard at constant production rates or at varied rates. Varied-rate practice enhanced motor learning by reducing the novices' finger movement variability, similar to how novice typists practice different combinations of successive finger keystrokes.

In sum, music learning improves with the accumulation of instances, consistent with Logan's Instance Theory. Considering the variability in different music performance situations (different notated scores, emotional expression, tempo changes) and the inefficiency of storing numerous instances due to memory constraints, this highlights the need for flexible motor programs, consistent with Schmidt's Schema Theory. Thus, the Schema Theory complements the Instance Theory by explaining for how musicians develop fine motor skills that allow for adjustments of motor programs to accommodate diverse performance conditions.

Adams' Closed Loop Theory

Parallels also exist between Instance Theory (Logan, 1988; 2002) and Adams' (1971) Closed-Loop Theory, which suggests that motor actions are regulated by continuous feedback. According to Adams, each action execution creates a perceptual trace in the central nervous system, and with practice, these traces accumulate, expanding the distribution of perceptual traces to include both correct and incorrect action executions. Motor learning occurs when these memory traces form a distinct modal value representing the correct motor command, reinforced by repeated accurate attempts and resistant to forgetting. This modal perceptual trace enables continuous analysis, identifying and correcting discrepancies between intended and actual movements through sensory input (Adams, 1976).

Similarly, Logan's Instance Theory (2002) posits that practice creates memory instances with each action, which accumulate over practice. Both frameworks emphasize that repeated practice strengthens internal representations, whether as perceptual traces or memory instances, resulting in more accurate action execution. Tapp and Logan (2011) assessed whether information from visual feedback influenced skilled typists' performance. Typists performed with one hand or two hands while their vision of their hands and keyboard were open or blocked. Performing with one hand slowed typing relative to two hands, and viewing the hands actually slowed typing relative to no visual feedback. Viewed through the lens of Adams' closed-loop theory of motor learning, Tapp and Logan's findings suggest that typists relied on alternative sources of information including kinesthetic memory traces available during the task.

When musicians learn a novel musical piece, they accumulate instances in memory that incorporate auditory, visual, and kinesthetic information. For example, skilled pianists' sensory information from finger accelerations at the point of key contact are associated with the temporal accuracy of performance (Goebl & Palmer, 2008), and sensory information from production experience influences later perception (Mathias et al., 2015). Closed-loop theory may not be the ideal framework for music performance, however, as it suggests that changes in sensorimotor feedback should disrupt performance, which is not always true (Finney, 1997); for example, removal of auditory feedback in well-learned performance has remarkably few effects on performance timing and intensity (Finney, 1997;

Finney & Palmer, 2003). Similar to Adams' model, memory traces based on auditory feedback are crucial during learning (Finney & Palmer, 2003) and accumulate over practice to improve the accuracy and fluidity of musicians' execution (Reybrouck & Schiavio, 2024). In sum, these findings highlight the importance of integration of sensory feedback and motor practice early in attaining music performance skills, fostering precise performances through the continuous reinforcement of memory traces.

Eye-hand coordination

Another notable parallel arising relevant to motor learning is the findings from eye-hand coordination tasks, in which some manipulation to (visual or auditory) perceptual information is seen in hand movements (by typists or musicians). The eye-hand span measures the span of time from visual stimulus presentation (eye) to execution of a motor response (hand). Eye-hand coordination measures are of particular interest in music performance that relies on music notation (ie, when musicians are not performing from memory). Logan (1983) revisited the eye-hand span equation in touch typing, defined as the number of letters per second (which is the reciprocal of the execution cycle time multiplied by the pre-execution cycle time). He argued that while increasing typing speed can create pauses, these pauses decreased as typists acquired skill due to parallel processing of the upcoming letters during the error analysis. This led to questions about the stopping span of the hand and eye (how quickly the two would cease movement, once the error was identified). Using the well-known stop-signal paradigm (Verbruggen & Logan, 2008), Logan estimated the processes responsible for stopping eye movements and stopping hand movements. The stop-signal reaction time, representing the latency of the stopping process, was shown to be shorter for eye movements than for hand movements (Boucher, Stuphorn, Logan, Schall, & Palmeri, 2007; Logan & Irwin, 2000).

Several studies of eye-hand span tasks in music performance have shown that the eye processes information a few items ahead of the hand, a distance that increases with musical expertise (Gilman & Underwood, 2003; Sloboda, 1983). Truitt, Clifton, Pollatsek, and Rayner's (1997) measurements of performers' eye movements indicated that eye fixations were focused on events for which performers were currently programming or soon to program a motor response. The less-skilled musician group had an eye-hand span of only one event, whereas the more skilled group had an eye-hand span of approximately two events. In another study, expert pianists engaged in two types of sight-reading with varying levels of complexity (easy and difficult scores), and eye-tracking measurements were employed to examine the eye-hand span (Imai-Matsumura & Mutou, 2023). The eye-hand span was shorter for pianists' performances of more difficult notated scores than for easier scores; furthermore, individual measures of working memory corresponded to individuals' eye-hand spans. The authors proposed that visual input from the music notation activates auditory working memory in chunks, which are converted into programmed finger movements. Chunking in working memory helps to minimize distractions from less relevant items that could interfere with effective motor programming (Imai-Matsumura & Mutou, 2023).

Chunking also plays a critical role in typing skills by enhancing processing efficiency, shifting from the production of individual letters to complete words. Skilled typing entails encoding groups of letters as higher-level processing units, which are then translated into individual keystrokes as lower-level units (Yamaguchi & Logan, 2016). In addition, changes to the usually available haptic feedback can alter lower-level processing. Yamaguchi and Logan (2014) showed that chunking at a higher hierarchical level (outer loop) was not disrupted when the inner loop slowed down due to the unusual haptic feedback at a lower level, pointing again to the independent processes occurring at the different hierarchical levels.

Skilled music performance also entails hierarchically ordered levels of information, including higher levels, such as openings of important musical melodies, and lower levels, such as specific chords or cadences (Williamon, Valentine, & Valentine, 2002). Interview studies of an expert cellist demonstrated a hierarchical memory structure, with recall of both structural and expressive cues in a hierarchically nested representation (Chaffin et al., 2009). Studies of errors indicate that skilled musicians recall more accurately phrase beginnings and endings (important boundary elements) than the middle events (Palmer & van de Sande, 1995). Models of expressive timing indicate that the amount of phrase-final lengthening corresponds to the hierarchical embedding of each musical phrase (Todd, 1987). Similar to Logan’s theory, these findings indicate that skilled musicians maintain a hierarchical structure in which skill acquisition incorporates larger and larger units.

In sum, eye-hand spans measured in novices' typing and music performance tend to show relatively short windows by which the eye advances beyond the hand; as expertise increases, producers tend to look more events ahead of their motor responses. Logan’s Instance Theory parallels key motor learning approaches by emphasizing the creation of distinct instances of representations during skill acquisition, while also shifting the execution of skilled actions to automatic control, minimizing top-down cognitive control while increasing chunk-processing efficiency.

B. Serial order in typing and music

The goal-directed behaviors of typing and music performance contain similar motor demands: many events must be planned and executed per second, with high spatial accuracy. These requirements are enabled in typewriter keyboard layouts that influence the finger-to-position mappings, and in acoustic musical instruments that influence finger-to-position mappings. With the advent of computers, it is possible for people to speak, type, and make music without regard to finger movements. Human memory constraints on serial order, however, remain whether an individual uses a typewriter or speech-to text conversion, or the musical equivalents. Both written language and notated musical compositions require exquisite memory for serial order. Errors of serial order, the focus of Logan’s typing skills research as well as music performance research, indicate some deep parallels in human memory constraints.

First is the general principle that conceptual similarity between any two items in the same sequence erodes with distance between those items (Logan, 2021). Similar to music errors, typing errors tend to reflect items intended for nearby in the same sequence. This memory constraint can be seen in speech errors, typing errors, music errors, and errors in other action sequences (Dell, Burger & Svec, 1997; Norman, 1981; Palmer, 2005). In music, for example, an intended melody **C-A-A-C- D-G** from the opening tones of the song "Hey Jude" (by P. McCartney and the Beatles, 1968) may be produced as C-A-A**-D** as a consequence of the adjacency (short serial distance) between the 4th intended tone C and the error outcome D, intended to occur on the 5th tone. In contrast, the same sequence **C-A-A-C-D-G** of tones is less likely to elicit an error on the second tone, such as C-**G;** this is due to the increased serial distance between the 2nd intended tone A and the error outcome G, intended to occur on the 6th tone. Logan's elegant hierarchical model of cognitive control includes a temporal reduction in item similarity, the farther the serial distance between those items. This reduction in item similarity over increased sequence distances is considered to be context-specific (i.e., dependent on the serial order of the sequence) and thus differs from errors that arise from similar spatial positions on a typing keyboard (for example, an index finger pressing the letter "R" instead of "F"), or slips of a finger on a piano key to a spatially adjacent key.

A second point of similarity across typing and music domains is the hierarchical distinction between higher conceptual (word) and lower execution (finger-letter) levels of analysis at the heart of Logan's cognitive control model. Both typing and music performance require a well-learned finger-to-key (or hole on some musical instruments) mapping. This mapping, specific to each keyboard layout, is the same for all typed sequences. This mapping, also specific to each musical instrument, is more probabilistic and sometimes allows different finger-to-key/hole movements to produce the same pitch. Despite this distinction, measures of speed and accuracy tend to generate different constraints at the lower level than those seen at the higher level. For example, in the music domain, pianists learn melodies first with their right hand (whether they are right- or left-handed) and later add the left hand.

Skilled pianists tend to make errors more often with the left hand than with the right hand, also regardless of handedness (Palmer & van de Sande, 1993).

This execution-level constraint is independent of (does not interact with) the similarity-based constraints on serial ordering of pitches. Similar to the cognitive control proposals of Logan and Crump (2011), this independence suggests that the cognitive constraints at a higher conceptual level do not interact with the execution-oriented constraints at the lower level. Transfer of learning in music performance also supports a hierarchical distinction between conceptual and execution-based processes (Palmer & Meyer, 2000); execution-based transfer is indicated when musicians who learn to perform a melody with one set of finger movements can perform quickly a different melody (set of pitches) with the same set of finger movements. Conceptual transfer is seen when musicians who learn to perform one melody (set of pitches) with one set of finger movements can perform quickly the same melody (set of pitches) with different finger movements. Only skilled musicians demonstrate the conceptual transfer, whereas both skilled and novice musicians demonstrate an execution transfer (Palmer & Meyer, 2000).

There are important distinctions between typing and music that influence serial order as well. Palmer and Pfordresher (2003) proposed a related mathematical model of serial order in music performance that followed the same general principle that conceptual similarity between any two tones erodes with distance between those tones. The rate of similarity reduction over distance was a function of not only serial distance but also time elapsed (measured by rate or # events per unit time). This parameter difference reflects the fact that music is not a speeded task like typing but instead has specific rates or tempi at which tone events should be produced (Palmer & Pfordresher, 2003). This rate parameter is part of a general performance context that applies equally to the entire sequence (and thus may not be considered contextual in Logan's sense). One interesting avenue for future research is whether a rate parameter is necessary to account for conceptual similarity in serial ordering in musical tasks that are speeded (ie, more similar to copy-typing), or alternatively, whether Logan's model would then account for serial ordering errors in speeded music tasks.

Another distinction that can influence serial order is the rate of repeating items in typing (and language) versus pitch repetition in music. Repetition rates of items in event sequences create both memory advantages (such as rhymes that aid memorized poetry; Rubin, 1995; Rubin & Wallace, 1988) and memory disadvantages (such as typographical errors that repeat high-frequency words like "the"). Music of all cultures features a small set of pitches that repeat often within the same sequence (one estimate is every 4-5 events; Palmer & van de Sande 1993), more often than letters tend to repeat in written text. Models of music perception weight heavily the tonal and harmonic relatedness perceived between musical pitches in a melody or musical piece (cf. Bharucha & Stoeckig, 1986; Krumhansl, 1990; Shepard, 1982). It is notable, however, that music performance does not require that the same pitch be produced with the same timing or motor movements (unlike typing, where each letter is controlled by the same finger and hand).

Models of serial order in music performance (Pfordresher, Palmer & Jungers, 2007; Palmer & van de Sande, 1993) include another measure of item similarity based on musical meter: the regular alternation of strong and weak beats in Western tonal music that influences perceived similarity (Prince, 2014). In music, serial ordering errors often reflect similarity in metrical accent: a strong tone interacts with another strong tone, and a weak tone interacts with another weak tone. Because Western music is built on metrical frames (similar to those proposed for speech; Dell, 1986), this means that errors based on metrical similarity will not erode over serial distances but instead show a regular pattern of interaction at serial distances of every 2 (binary meters) or every 3 (ternary meters) tones. An interesting avenue for future research might be how typists produce tongue-twisters designed to repeat phonemes at regularly recurring serial distances, such as "She sells sea shells" in which the S-E and S-H serial orderings are altered from one word to the next. Based on the serial ordering models proposed for music that contains high pitch repetition rates (Palmer & Pfordresher, 2003; Pfordresher et al., 2007), the predictions would include similarity metrics based on the repetition rates among similarity-related letters. Thus, the typed phrase “she sells sea shells” should generate more -E- and -H- errors in the tongue twister context than a typed phrase containing the same letters that did not feature as much repetition, such as “she sold sea salt”.

Finally, we consider the types of serial ordering errors observed in typing, speech, and music. Similar to studies of speech (Dell, 1986), Logan (2018) coded additions, deletions, exchanges, and substitutions of letters typed in the incorrect position. Only letter errors that occurred within a word were considered; in most error analyses for speech and music, the distances between target (correct event) and intruder (for additions and substitutions) are typically computed over an entire phrase or sequence. Although exchange errors occur across words in speech (Dell, 1986), Logan’s (2018) typing errors showed that exchange of neighboring letters was rare, while additions were most common. Exchange errors are rare in music as well (Palmer, 1989), perhaps due to the metrical framework of alternating strong and weak beats that makes neighboring pitch events less similar metrically. These error comparisons across domains suggest that the inner loop processes (phonetic level in speech; finger-key level in music), similar to Logan’s finger-key inner loop for typing, define domain-specific constraints while the conceptual outer loop may share similarities across domains. An example is the impact of high-level concepts formed by phrase boundaries in speech and music that reduce interactions among events that are separated by a phrase boundary (Palmer & van de Sande, 1995).

C. Speed-accuracy relationships

Logan and colleagues (Crump & Logan, 2010; Yamaguchi, Crump & Logan, 2013) have also addressed how cognitive skills that become automatic can remain flexible and adaptive. They explained this paradox in the context of hierarchical control between 2 feedback loops: an outer loop (central process that organizes the intention or plan) and an inner loop (series of keystrokes to produce a word), with strategic weighting between the two to produce accurate or fast performance. Analyses of keystroke timing and errors suggested that skilled typists can focus on the outer loop while allowing the inner loop processes to run automatically. Evidence in music and typing tasks support the distinct levels; skilled typists do not look often at their fingers, similar to how musicians can sustain their attention on reading a notated musical score without looking often at where their fingers are placed on an instrument. As in typing, skilled musicians show highly adaptive and flexible performance (Scheurich, Zamm, & Palmer, 2018; Scheurich, Pfordresher & Palmer, 2020) that is especially important in order to remain synchronous with other musicians who often change their tempo within a musical sequence, whether signalled through nonverbal visual cues or only via auditory cues.

Logan and colleagues tested whether matching a given typing rate affects the speed/accuracy relationship. Yamaguchi, Crump and Logan (2013) introduced different pacing cues to skilled typists: a metronome that paced when typists should produce the next letter; a speedometer (words/minute); or a color-based cue that changed from black to blue to indicate the next text to type. The color cue generated better pacing than the metronome or speedometer cues, which the authors attributed to possible difficulties merging the auditory metronome with the visual text. There are few comparable studies that manipulate the notated layout to measure effects of pacing on music performance; one exception is the windowing method used to estimate eye-voice span that has been extended to eye-hand span in piano performance (Furneaux & Land, 1999; Sloboda, 1974). Future directions might apply the color and speedometer pacing cues to music performance based on notation reading. Predictions from Logan and colleagues suggest that integrating the auditory metronome with the visual information should be most difficult on correct pacing. However, prior findings in music performance suggest that the metronome should generate the most accurate pacing, regardless of the performance from notation. Whereas musicians often hear a metronome or see a conductor's baton that signals the pace of individual tones, typing is not often paced at the level of individual keystrokes.

Important differences in production rates impact the speed-accuracy relationships found in typing and music performance. Musical tones must be produced at specific points in time; this pacing aspect of musical tempo creates different demands from a speeded task like typing and may explain why few speed-accuracy models have been applied to music. Pfordresher, Palmer and Jungers (2007) tested a speed-accuracy model of music performance. The first assumption, that event retrieval of sequential tones is based on activations of surrounding contextual events, is similar to Logan's (1990) obligatory encoding assumption that the item is encoded with its context. This contextual retrieval was influenced by musicians' production rates such that both the accessibility of distant sequence items and the overall accuracy decreased at faster production rates. Model fits to speed–accuracy data and to serial ordering errors of pianists who produced music at 8 different rates suggested that individuals' working memory constraints influenced the retrieval of serial order by altering the similarity-based contextual effects; the greater the working memory constraint, the larger the contextual retrieval activation (Pfordresher et al., 2007). Thus, this finding resembles the hand-eye span effects in typing and music, further supporting the role of context in sequence encoding and retrieval.

Speed-accuracy relationships in music performance are also influenced by performers' motor dexterity and domain-specific musical skills (Pfordresher et al., 2007). Individuals with lower finger dexterity (corresponding to performers' tempo error relative to the cued production rate) or with lower performance skills (corresponding to the number of repetitions needed to reach an errorfree performance) showed greater reductions in item activation relative to those with greater dexterity or musical skill. Although typists' finger dexterity and skill levels have long been discussed (Walker & Adams, 1934), they have not yet been incorporated in speed-accuracy frameworks, to our knowledge. Thus, this may be a fruitful direction for music performance research to influence related skills such as typing. The next section considers future directions suggested by Logan's work.

D. Future directions

Several aspects of skill acquisition are not yet well-understood; here we consider topics posed by Logan's work that may be applied to the domain of music. Those topics include inhibitory processes in error monitoring and the balance between controlled and automatic processes. The monitoring, retrieval, and neurological mechanisms for identifying incorrect (errorful) performance have yet to be compared across different skills. It is possible that inhibitory mechanisms, important for preventing errors in speeded performance, may vary with the task goals. Several studies focus on post-error slowing, or the slowing down of production rate following an error. One feature of Logan's context retrieval and updating model is the (mis-) comparisons between memories for correct and errorful behaviors. Typists slow dramatically in typing speed once they make an error (Logan & Crump, 2010; Salthouse & Saults, 1987). Much of this slowing is considered to be strategic, based on findings that post-error slowing is reduced when the experimenters' instructions emphasize that typists should type quickly and not correct errors (Yamaguchi, Crump & Logan, 2013). Crump and Logan (2013) have suggested that instructions to not correct errors may require that typists inhibit their automatic tendencies to correct those errors for example by pressing the backspace key (Crump & Logan, 2013), whereas musicians cannot remove an error once it is sounded. Logan (2018)'s context retrieval and updating model explains post-error slowing as arising because a context that includes an error will not match any memories for correct stored contexts and thus processing delays result.

Music performance often requires a strong inhibition of any tendency to correct errors for several reasons. One reason why is to allow musicians to prioritize staying in time together; any pauses necessary to correct errors in solo or group performance will disrupt the metrical structure or alternating stress pattern that guides when upcoming events (tones or chords) should be produced. Ruiz, Jabusch, and Altenmüller (2009) and Strübing, Ruiz, Jabusch, and Altenmuller (2012) reported post-error slowing in musicians' occasional errors; they did not manipulate production rate, and so comparisons with Logan's (2018) findings are limited. One extension of the context retrieval and updating model would be to test whether increased production rates similarly reduce the post-error slowing in music performance. The outcome is not obvious, due to extensive work in music performance that documents behavioral and neural changes that occur during sequence events preceding a production error (Drake & Palmer, 2000; Maidhof et al., 2009; Palmer, Mathias & Anderson, 2012; Ruiz et al., 2009). If pre-error monitoring is influenced by the units being planned or by chunking processes (such as phrases), then post-error slowing may be a vestige of the monitoring processes that slow during sequence events just prior to a produced error, instead of (or in addition to) delays that result from mismatched (errorful) contexts with memory retrieval.

A second reason that music performance requires the inhibition of a tendency to correct errors is due to the high repetition rate of pitches. Repetition is rampant in typing and music; individual keystrokes corresponding to letters (26 in total) repeat often in a typed passage, and individual pitches in a single-line melody (often 7-9 total) tend to repeat even more often (Margulis, 2013). In one estimate of simple musical melodies, pitches repeated on average every 4-7 events; thus, a fast inhibitory process may interfere with mental plans to produce that pitch in the near future (Palmer & Pfordresher, 2003). An absence of musical "exchange" errors, in which a future event is swapped in time with a current event, supports the notion that musical pitches must be repeated quickly without inhibitory processes. An interesting avenue for further investigation would be to test typists' and musicians' inhibitory processes for stimulus materials with altered repetition rates.

Dual-processing frameworks and domain expertise

Logan's characterization of typists' inner and outer loops aligns with other dual-processing frameworks that distinguish between automatic and controlled processes (Schneider & Schiffrin, 1977), or similar terminologies that contrast intuitive, effortless, unconscious and automatic processes with analytical, effortful, conscious and controlled processes (Evans, 2008), a distinction that has been applied to music performance as well. Domain expertise, such as proficiency in improvisational music

performance, shifts the balance between automatic and controlled processes. Expert typists engage automatic control systems, without needing to focus on every sequence of motor commands, allowing top-down processes to focus on monitoring intended goals (Logan, 2018). Expert musicians primarily rely on automatic processes for performance from memory, whereas novices depend more on deliberate cognitive control (Chaffin, Imreh, & Crawford, 2002). An important domain distinction, however, is that the rhythm and pressure of keystrokes in typing do not affect the meaning or effectiveness of the communication. In contrast, musical rhythm and tone intensity resulting from key pressures are integral to expressive goals that develop with musical expertise (Bangert, Schubert, & Fabian, 2014).
Norgaard (2019) has suggested that error correction operates differently in automatic and controlled processes during musical improvisation, but experimental confirmation of a dual-process framework for music performance has not yet been proposed. For example, Logan's findings could be extended by instructing musicians to attend to lower-level features such as how often each finger is used in performing a melody, to test the prediction that more disruptions should result for individuals with increased skill levels. Logan and colleagues' research with skilled typists (Logan & Crump, 2009; 2010) paves the way for testing automatic and controlled processes in music performance; an example is the ability of a clarinetist to continue performance at the same pace even after errors are experimentally inserted on a musically notated screen (ie, an undeceived inner loop), while the error-monitoring eyes are misled into attributing those insertions as self-generated errors (ie, a deceived outer loop).

Music performance studies provide partial evidence for a dual-processing framework consisting of automatic processes and controlled processes. Pfordresher and Beasley (2014) investigated perceived differences between self-generated and experimentally inserted mistakes as adults (not trained on piano) learned to play simple melodies from notation. The participants heard altered auditory feedback in which the pitch feedback was either normal or was shifted to match a pitch that had occurred two keypresses earlier. This manipulation led the participants to overestimate self-generated errors and to attribute experimentally inserted errors to themselves, paralleling the self-attributions of experimentally induced errors in typing (Logan & Crump, 2010). When participants performed a concurrent task that required executive processes while auditory feedback was used to add errors, the tendency to overestimate errors remained, suggesting that the error monitoring processes were not directly controlled. Maidhof, Vavatzanidis, Prinz, Rieger, and Koelsch (2009) provided similar evidence in an EEG-based study of pianists' errors. EEG responses were measured during pianists' self-generated errors as well as errors introduced through altered auditory feedback, while the pianists counted the number of incorrect pitches they heard. Event-related negativities were found for self-generated errors but not for feedback-induced errors, indicating that different processes distinguished between self-generated and externally-inserted errors. These findings mirror Logan and Crump's (2010) findings in which typists' hands slowed down after self-generated errors but not after experimentally induced errors, illustrating the need to posit two levels of control, one automatic for experimentally induced errors and one controlled for self-generated errors. What remains to be determined is how electrophysiological markers during production errors (typing and music performance) provide evidence for the operation of both levels of control (see Servant, Chase, Woodlawn & Logan, 2018, for related evidence from memory recognition tasks).

In sum, Gordon Logan's legacy in memory, attention, and motor learning in the domain of typing bears important similarities and differences to the same processes in music performance, another complex skill common in humans. This comparison suggests a broad and lasting impact for the types of questions that psychologists should ask of executive control, such as error monitoring and domain expertise, and motor learning theory, including hierarchical loops that distinguish automatic and controlled processing. Within the framework of music performance, we have proposed several avenues for testing the consequences of Logan's theoretical discoveries that may ensure their lasting influence.

Acknowledgements

This work was supported in part by an NSERC Discovery Grant to C Palmer and by a HORIZON TMA MSCA Postdoctoral Fellowship (EU) to A. Smykovskyi. We thank Sandra Kuliver and Wenbo Yi for comments on an earlier draft. Correspondence can be addressed to caroline.palmer@mcgill.ca.

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Table 1. Similarities and differences in motor learning, serial order constraints, and speed-accuracy tradeoffs proposed for Typing (T) and Music Performance (M).

Motor Learning		**Serial Order Constraints**		**Speed-Accuracy Tradeoffs**	
Similarities	**Differences**	**Similarities**	**Differences**	**Similarities**	**Differences**
Flexible item representations arise from many contextual instances	Motor skill competency attained earlier (T) or later (M)	High spatial accuracy in item execution	Higher temporal accuracy required in item execution (M)	Distinct processing levels (inner loop, outer loop) influence tradeoff	Temporal task demands (T= speeded task; M= rhythmically timed task) influence tradeoff
Item representations include multi-sensory information	Feedback from sensory information less critical after learning (M)	Conceptual similarity erodes over larger sequence distances	Conceptual similarity influenced by sequence rhythm (M)	Speed-accuracy influenced by contextual event activations	Speed-accuracy influenced by individual differences in motor dexterity (M)