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Effects of Practice Variability and Distribution of Practice on Musicians' Performance of a Procedural Skill

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Effects of Practice Variability and Distribution of Practice on Musicians' Performance of a Procedural Skill

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Dedication

For Abbie and Baby Simmons

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Effects of Practice Variability and Distribution of Practice on Musicians' Performance of a Procedural Skill

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I designed three experiments to determine how procedural memory consolidation in a music task is affected by practice under different conditions of speed regulation and different time intervals between practice sessions. Ninety-two nonpianist musicians practiced a 9-note sequence with their nondominant hand on a digital piano in three sessions, each of which comprised 3 blocks of 15 performance trials. In Experiment 1 (n = 31), participants were instructed to perform as quickly and accurately as possible but determined their own tempos in each trial. In Experiment 2 (n = 31), three defined practice tempos (M. M. = 52, 72, and 92) were externally regulated in a stable practice procedure in which tempo changed between, not within, blocks. In Experiment 3 (n = 30), the same three tempos were externally regulated in a variable practice procedure in which practice tempo changed from trial to trial within each block. In each experiment, three different groups' practice sessions were separated by either 5 min, 6 hr, or 24 hr.

Consistent with previous descriptions of procedural memory consolidation, the results of Experiment 1 show that note accuracy improved significantly between Sessions 1 and 2 only when the sessions were separated by a 24-hr interval that included sleep; performance speed improved in all groups between Sessions 1 and 2, and between Sessions 2 and 3 when sessions were separated by 6 or 24 hr. In Experiment 2 (stable practice) there were significant improvements in note and tempo accuracy between Sessions 1 and 2 when those sessions were separated by 5 min or 6 hr, but not when the sessions were separated by 24 hr. In Experiment 3 (variable practice), note accuracy improved between Sessions 1 and 2 only when the sessions were separated by a 24-hour interval that included sleep; there were no significant improvements in tempo accuracy, perhaps due to the high physical demands of matching varying target tempos in successive trials. These results demonstrate that motor skill learning in music is affected by the time interval between practice sessions, and that the effects of distributed practice are dependent upon practice conditions.

Table of Contents

List of Tables

List of Figures

Chapter I: Introduction

The goal of instrumental music teaching is to improve the performance of developing musicians. Most teachers agree that engaging in physical practice is the most efficient and effective way for students to improve performance skills, and that knowing *how* to practice is a critical component of becoming an accomplished performer. Although independent practice plays an important role in improving performance skills, practice behaviors and practice strategies have not been thoroughly investigated in the music learning literature.

Observing professional and advanced musicians (e.g., graduate students in music performance that have reached near-professional levels of skill) engaged in practice is a logical way to learn about effective practice, as advanced performers have reached the highest levels of skill in our discipline. Detailed descriptions of professional and advanced musicians' practicing (Chaffin & Imreh, 1997, 2001; Chaffin, Imreh, Lemieux, & Chen, 2003; Hallam, 2001; Miklaszewski, 1989; Nielsen, 1999a, 1999b, 2001, 2004; Williamon, Valentine, & Valentine, 2002) identify key behaviors of experts: they engage in goal-directed practice, they use effective practice strategies to improve performance, they monitor their progress during practice, and they adjust their implementation of practice strategies when they perceive their current course of action to be ineffective.

Even in initial stages of acquisition, professional and advanced musicians play large sections of pieces at tempos close to performance tempo (Duke, Davis, & Simmons, 2004; Miklaszewski, 1989; Nielsen, 1999a); they allow an aural image of a piece to guide physical practice (Chaffin & Imreh, 2001; Chaffin et al., 2003; Miklaszewski, 1989); they employ extensive repetition during practice (Maynard, 2006); they address errors immediately and thoroughly so they do not reoccur (Chaffin & Imreh, 2001; Duke et al., 2004); they practice technically demanding passages in chunks (Chaffin & Imreh, 2001; Maynard, 2006; Miklaszewski, 1989; Nielsen, 1999a); they practice those chunks at varying tempos (Duke et al., 2004; Miklaszewski, 1989; Nielsen, 1999a); and they recontextualize that material before moving on to something new (Duke et al., 2004; Miklaszewski, 1989). Taken together, these studies illustrate that professional and advanced musicians engage in thoughtful practice that is strategically designed to accomplish specific performance goals.

Music learning research that has examined the practice behaviors and strategies of inexperienced and so-called "developing" musicians makes clear that developing musicians typically do not practice like professionals and advanced musicians (Lehmann & Ericsson, 1997; Pitts, Davidson, & McPherson, 2000). Developing musicians tend to ignore mistakes in their practice. When errors are addressed, they are not addressed effectively enough to eradicate errors in subsequent performance (McPherson & Renwick, 2001). Repetition of material does not occur to the extent observed in the practicing of more skillful musicians (Maynard, 2006). Developing musicians tend to "play through" music, applying little or no metacognitive skills in their practice (McPherson & Renwick, 2001).

Practice strategies employed by professional and advanced musicians have been imposed on developing musicians with some success. Developing musicians benefit from structured, goal-oriented practice (Barry, 1992; Puopolo, 1971); from physical engagement with their instrument (Lim & Lippman, 1991); from mental practice alone (Coffman, 1990; Ross, 1985) and combined physical and mental practice (Theiler & Lippman, 1995); from listening to models (Goins, 2006; Henley, 2001; Hewitt, 2001; Lim & Lippman, 1991; Puopolo, 1971; Rosenthal, 1984; Rosenthal, Wilson, Evans, &

Greenwalt, 1988; Theiler & Lippman, 1995); and from distributing practice over time (Rubin-Rabson, 1940; Simmons & Duke, 2006).

Although music teachers may suggest to developing musicians that they distribute their practice over time, there is little empirical evidence in music literature that describes the effectiveness of this strategy or explains *why* this strategy may be effective for developing musicians. Recent research in other domains of human learning has demonstrated that distributed practice can enhance learning. Simmons and Duke (2006) obtained similar results in the context of music performance.

Distributed practice has received considerably more attention by researchers of human movement and psychology, albeit in different contexts than those typically discussed in music research. Even though most of this work involves the acquisition of simpler motor skills than those involved in music performance, the principles of human learning and memory that have been described in these investigations offer a wealth of information about the cognitive and physical processes that underlie performance improvements of motor skills in general. These ideas can inform what musicians do and what teachers instruct developing musicians to do.

HUMAN MOTOR LEARNING AND MEMORY RESEARCH IN OTHER DOMAINS

Researchers who study human movement have examined how the content of practice affects the acquisition and improvement of motor skills and the development of motor skill memory. Many of their studies required learners to practice relatively simple motor skills (i.e., skills that have one degree of freedom, can be acquired in one practice session, and are typically not skills executed outside of laboratories); much less research is done with complex motor skills (i.e., skills that have multiple degrees of freedom, require multiple practice sessions for skill acquisition, and are sometimes skills people engage in as a part of life), a category under which music performance inarguably falls (Wulf & Shea, 2002).

Practice Variability

Over the past 32 years, motor learning research has demonstrated that including variability in the acquisition and continued practice of new motor skills affects the way motor skills are encoded into memory and recalled in subsequent practice. Variability in motor skill execution is systematically imposed on learners in these investigations; learners either practice slightly altered versions of the same kind of movement (e.g., hitting a curveball and a fastball) or they practice the same movement under slightly different performance parameters (e.g., executing the same finger-tapping sequence at different speeds). Learners recall the new skill in a retention test and complete a transfer test at least 24 hours after acquisition practice. Comparisons are then made between performances of learners who executed identical movements under identical performance parameters during practice (stable practice) and performances of learners who negotiated a degree of variability in the movement itself or in performance parameters during practice (variable practice).

Put most simply, motor learning research consistently demonstrates that variable practice enhances the retention and transfer of simple motor skills to a greater extent than does stable practice (Albaret & Thon, 1998; Li & Wright, 2000; Pollock & Lee, 1997; Shea, Kohl, & Indermill, 1990; Shea, Lai, Wright, Immink, & Black, 2001; Simon & Bjork, 2001; Tsutsui, Lee, & Hodges, 1998; Young, Cohen, & Husak, 1993); however, research that explores complex skill learning demonstrates that the benefits of variable practice over stable practice are mediated by skill complexity and learner sophistication (for reviews, see Guadagnoli & Lee, 2004; Wulf & Shea, 2002). It may seem counterintuitive that executing skills under variable conditions yields enhanced performance at subsequent retests more so than does executing skills under stable conditions, particularly when error rates are considered. Learners who acquire skills under variable conditions unsurprisingly make more errors in practice than do learners engaged in stable practice (Giuffrida, Shea, & Fairbrother, 2002; Li & Wright, 2000; Pollock & Lee, 1997; Shea et al., 1990; Shea et al., 2001; Simon & Bjork, 2001; Tsutsui et al., 1998; Young et al., 1993). How then could more errorful practice yield superior performance at retest? Researchers in human movement propose that the extent to which learners are cognitively engaged during practice explains the benefits of variable practice *and* the differences between variable practice effects observed with simple and complex motor skills.

Variable practice requires more cognitive engagement than stable practice. When movement structure and performance parameters remain the same from trial to trial, the amount of cognitive effort learners must exert to execute skills decreases over multiple repetitions; in other words, skill execution to some extent requires less attention. Varying movement structure or performance parameters between trials maintains higher levels of cognitive effort throughout practice. Cognitive processing must change from trial to trial, thereby increasing cognitive demands placed on learners. As a result of heightened cognitive engagement throughout acquisition practice, learners who engage in variable practice demonstrate enhanced performance in subsequent retests more so than do learners who engage in stable practice.

Learners demonstrate varying levels of ability when acquiring new skills and consequently respond to skill complexity somewhat idiosyncratically; in general, learning is optimized when the difficulty of a given task matches the sophistication of learners and when the degree of variability in practice is modified according to that relationship. More sophisticated learners (those who have some degree of familiarity or skill with the task to be acquired) are able to negotiate more complex skills (high cognitive demands) or a greater degree of variability in practice (high cognitive demands) than are less sophisticated learners. The delicate and poorly defined relationship between task complexity and learner sophistication makes it difficult to effectively match learner sophistication with appropriate levels of task complexity and practice variability. Demanding too much cognitive effort from one component overloads the learner and diminishes the beneficial effects of including variability in practice.

Although there is as yet no clear experimental evidence demonstrating that systematic variation in practice enhances music performance skills, practicing with variations in performance parameters has long been a typical part of musicians' practice routines. Based on the research described above, it seems logical that musicians who possess different levels of sophistication would respond differently to variability in practice, particularly when executing movements of different complexity levels. Learning to perform on a secondary instrument, for example, inarguably requires the simultaneous execution of many complex motor skills (e.g., forming an embouchure, creating sound, moving fingers to produce melodic lines). The development of such novel skills in well-trained musicians is affected by task complexity and practice variability in ways that have been unexplored to date.

Distributing Practice Over Time

Research in human movement has demonstrated that learners who distribute practice over time (i.e., dividing practice trials across multiple sessions that span several days) perform better than do learners who engage in massed practice (i.e., completing all practice trials in one session on one day) when skills are recalled at least 24 hours after practice ends (Dail & Christina, 2004; Donovan & Radosevich, 1999; Lee & Genovese, 1988; Lee & Wishart, 2005; Shea, Lai, Black, & Park, 2000). In an effort to explain *why* distributing practice across time enhances performance skill and memory more than massed practice, researchers in human movement have drawn upon explanations first proposed by psychologists (for reviews, see Lechner, Squire, & Byrne, 1999; McGaugh, 2000), which suggest that enhancements in performance are behavioral manifestations of neurophysical changes in the brain during rest intervals between practice sessions. These biological processes, identified as *memory consolidation*, have yet to be clearly defined; however, it is now widely accepted that acquiring new motor skills and forming memories for those skills elicit structural and functional reorganization in the brain (Walker & Stickgold, 2006). A time course for skill acquisition and memory consolidation has been consistently demonstrated in neuroscience literature that examines simple motor skill acquisition and performance in a population of learners who have no prior experience with the task they are asked to learn.

Observed patterns of neural activity change over time as learners engage in skill acquisition. Learners experience a rapid improvement in skill execution when they first engage in practice of a new motor skill (Fischer, Hallschmid, Elsner, & Born, 2002; Karni et al., 1998; Korman, Raz, Flash, & Karni, 2003; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002). As these rapid improvements occur, neural activity that guides motor activity is modified (Floyer-Lea & Matthews, 2005). Neurons that fire together during repeated practice of a new motor skill begin to fire together more easily so that existing pathways become readily activated as practice continues (Karni et al., 1998; Kleim et al., 2004; Walker, 2005). Rapid improvements level off during acquisition practice, and performance gains are incremental by the end of the session. The refined pattern of neural activation that emerges at this point comprises a neural representation of the newly acquired motor skill.

Changes in memories for newly acquired skills occur when learners are not actively engaged in practice, an idea that seems contrary to commonly held views in music teaching and learning. Practice triggers the onset of memory consolidation, but the process continues after practice has ended (Luft & Buitrago, 2005). Memory consolidation is thought to occur in two stages (Walker, 2005): the first stage, *consolidation-based stabilization*, modifies neural representations of motor skills in ways that make memories resistant to interference and forgetting; the second stage, *consolidation-based enhancement*, yields enhancements in motor performance and memory.

Consolidation-based stabilization typically occurs in the wakeful hours immediately following practice. Wake-based consolidation makes memories resistant to interference from competing tasks (e.g., engaging in motor activity nearly identical to practiced tasks) and maintains performance gains achieved during acquisition (Fischer et al., 2002; Hotermans, Peigneux, Maertens de Noordhout, Moonen, & Maquet, 2006; Robertson, Pascual-Leone, & Press, 2004; Walker, Brakefield, Hobson, & Stickgold, 2003; Walker et al., 2002). The process of wake-based consolidation typically lasts up to four to six hours after active practice has ended. If this process is interrupted, performance of newly acquired skills can be impaired and their memories compromised.

Current theory suggests that consolidation-based stabilization is characterized by intermittent occurrences of task-related neural activity and by early protein synthesis in the brain (Peigneux et al., 2006). Imaging studies have demonstrated that brain activity during skill acquisition is different from patterns of brain activity elicited when skills are recalled after consolidation-based stabilization has occurred, which suggests that the memories for new skills are modified subsequent to active practice.

Consolidation-based enhancement depends on the chemical processes of sleep. Sleep-based consolidation enhances memories for newly acquired skills so that performance is significantly improved when skills are recalled. In other words, sleep enhances simple motor skill performance in the absence of additional practice (Brashers-Krug, Shadmehr, & Bizzi, 1996; Duke & Davis, 2006; Fischer et al., 2002; Fischer, Nitschke, Melchert, Erdmann, & Born, 2005; Hotermans et al., 2006; Karni et al., 1998; Korman et al., 2003; Kuriyama, Stickgold, & Walker, 2004; Maquet et al., 2003; Mednick, Nakayama, & Stickgold, 2003; Robertson, Press, & Pascual-Leone, 2005; Simmons & Duke, 2006; Walker, Brakefield, Hobson et al., 2003; Walker, Brakefield, Seidman et al., 2003). The chemical processes of sleep are thought to "clean up" neural activity that occurs during acquisition; in other words, processes that occur during sleep disengage neural networks that were active during acquisition but are not essential for optimal task performance (Benington & Frank, 2003). Sleep studies have demonstrated that patterns of brain activity engaged during new task learning are again active during sleep, as if the brain is "replaying" significant events of the day (Walker & Stickgold, 2006). More invasive work done with cats has clearly demonstrated that modifications of neural connections occur during sleep (Frank, Issa, & Stryker, 2001). Once again, it is clear that memories continue to be encoded and modified after practice has ended in ways that enhance performance when skills are recalled.

STUDY PURPOSE

The purpose of music practice is to improve performance skill as quickly and efficiently as possible. Instructors teach their students effective practice strategies in an effort to create independent learners who are able to improve skills in the absence of external guidance. Practice strategies mentioned in music literature have yet to be explored thoroughly in music performance contexts. Systematically varying motor skill execution during practice and distributing practice over time (which allows memory consolidation to occur) are two such strategies that have received little attention in music research, though motor skill research in other domains has demonstrated the effectiveness of these two strategies in improving motor skill performance.

Kinesiology and neuroscience research have demonstrated beneficial effects of distributed practice, most often with learners who have no prior task-related experience and who practice relatively simple motor tasks. Beneficial effects of distributed practice that includes sleep-based memory consolidation have also been observed with non-pianist musicians who engaged in self-regulated practice of a short sequence of notes on a keyboard (Simmons & Duke, 2006). It remains to be seen whether distributing practice across intervals of wake- and sleep-based consolidation will affect the way skills are learned and recalled when learners engage in externally regulated practice that includes systematic variation in task performance during practice.

The purpose of the present study was to examine the effects of wake- and sleep-based memory consolidation on musicians' retention of complex motor skills learned under self-regulated practice conditions and externally regulated practice conditions with systematic variations in performance speed. I sought to discover new information about the cognitive processes that underlie complex motor skill performance and provide functional information for increasing efficiency and success in motor skill learning.

This research addressed the following three questions:

1. Experiment 1: To what extent are complex motor skills affected by wake- and sleep-based consolidation processes in learners with extensive task-related knowledge and moderate levels of task-related skill?
2. Experiment 2: To what extent are consolidation-based enhancements affected by stable practice procedures, in which the speeds of learners' practice trials are externally regulated and practiced in a sequence that includes minimal variation in performance speed from trial to trial?
3. Experiment 3: To what extent are consolidation-based enhancements affected by variable practice procedures, in which the speed of learners' practice trials are externally regulated and practiced in a sequence that includes maximum variation in performance speed from trial to trial?

Chapter II: Review of The Literature

HUMAN LEARNING

Observable changes in patterns of human behavior are outward manifestations of neurophysical changes in the brain. The processes involved in learning, specifically, the encoding, storage, and retrieval of memories, are of interest to researchers in domains related to various aspects of human behavior. Understanding the cognitive processes that underlie memory formation illuminates how learners best acquire knowledge.

All that people know and are able to do is broadly classified into one of two categories of knowledge: declarative knowledge (e.g., facts and events) and procedural knowledge (e.g., physical and perceptual tasks). Declarative knowledge is further separated into two distinct categories. Episodic memory describes recall of specific events (e.g., the details of a first piano recital), whereas semantic memory refers to the recall of facts (e.g., the capital of Texas is Austin). Procedural knowledge is often revealed through the execution of perceptual and motor skills (e.g., playing a C major scale on the piano) and habits, by demonstrating learned associations between actions and consequences, and by demonstrating reflexive behavior (Squire & Zola, 1996).

Learners may acquire declarative knowledge with relatively few exposures to a stimulus and with very little rehearsal. The acquisition of procedural knowledge, though, typically requires longer periods of exposure and multiple repetitions of skills (i.e., practice). Playing a C scale on the piano beautifully (a procedural skill) requires more instruction and practice than does reciting the notes of the scale (declarative knowledge).

Procedural skill learning, particularly fine motor skill learning, is characterized by incremental improvements in performance that are brought about by practice and the passage of time (Karni et al., 1995; Karni et al., 1998). Research in neuroscience, psychology, and human movement has investigated the cognitive and physical processes that underlie performance improvements in motor skills, and has begun to explain how memories change over time and how the structure of practice affects learning. These investigations often study the acquisition of simple motor skills (i.e., skills that have one degree of freedom, can be acquired in one practice session, and are typically not executed outside laboratories); there is less research in procedural learning that considers complex motor skills (i.e., skills that have multiple degrees of freedom, require multiple practice sessions for skill acquisition, and are sometimes engaged in as a part of life) (Wulf & Shea, 2002), particularly the skills of music performance.

Music practice and performance have received some attention from psychologists, because examining the behavior of musicians in the practice room offers rich information to the study of human learning and memory. Instrumental music performance involves the execution of intricate fine motor movements that are planned and rehearsed extensively, are often coordinated between hands, and are sustained over long periods of time in one practice session. These complex skills are performed over professional musicians' life spans and reside in rich and varied contexts, making authentic music skills difficult to study systematically.

MUSIC PRACTICE

Musicians of all ages and skill levels engage in practice to improve the quality and fluency of their performances. Considering the importance of practice to the development and maintenance of performance skill, it is surprising that the details of practice (i.e., what goes on in practice rooms), particularly practice over extended periods of time, has been scarcely addressed in music research.

Complex motor movement planning and rehearsal occur simultaneously with complex auditory processing and discrimination in music practice. Advanced musicians develop auditory images (i.e., mental representations) of repertoire that are based on years of performance training and experience (Duke & Simmons, 2006). An advanced musician compares her auditory image of a piece she's learning with the sounds she hears in the practice room. Practice is directed at modifying and refining motor movements so that musical intentions are conveyed appropriately (Chaffin & Imreh, 2001; Chaffin, Imreh, Lemieux, & Chen, 2003; Miklaszewski, 1989).

In light of the extended, intensive practice that musicians undertake to achieve professional levels of performance (Ericsson, Krampe, & Tesch-Romer, 1993), examining the practice of professional musicians seems an advantageous starting place in gathering information about music practice (Chaffin et al., 2003). The fact that experts attain such high levels of skill indicates that their practice behavior functioned effectively in their development of skills.

Practice Strategies Observed in Cases Studies of Advanced Instrumentalists

Several case studies of advanced musicians (i.e., music performance majors who have reached near-professional and professional levels of performance) and professional musicians have been conducted in an effort to identify the mechanisms of practice that are consistently employed by the highest achievers (Chaffin & Imreh, 1997, 2001; Chaffin et al., 2003; Miklaszewski, 1989; Nielsen, 1999a, 1999b, 2001; Williamon, Valentine, & Valentine, 2002). In these investigations, musicians were observed as they practiced a new piece in preparation for performance and the strategies they employed during practice (i.e., systematic approaches to solving identified potential and existing performance problems) were identified and described.

Professional musicians systematically use a variety of physical and cognitive strategies to acquire a mental representation of a piece of music (i.e., an auditory image of the piece they will perform) and the motor skills required to execute performance so that the auditory image is realized (Chaffin et al., 2003; Miklaszewski, 1989). In fact, Chaffin et al. (2003) determined that the auditory representation of a piece guides physical practice from the initial reading to performance in concert. Auditory images of music are processed with different neural mechanisms than are motor skills, yet the findings described by Chaffin et al. (2003) and Miklaszewski (1989) suggest that advanced musicians' auditory and motor processing work together in initial stages of practice for the proper acquisition of new material.

After an initial reading of a score to be learned, advanced musicians begin to develop motor skills that are required to execute technical demands of the piece (e.g., notes, rhythms), which is unsurprising. In case studies of professional and advanced pianists, Miklaszewski (1989) and Chaffin and Imreh (2003) observed that a great deal of effort in the initial stages of practice was directed at deciding on fingering combinations for technically demanding passages. Once selected, fingering patterns remained fixed throughout practice (Chaffin et al., 2003; Miklaszewski, 1989; Nielsen, 1999a). Chaffin and Imreh (2003) described the importance of this strategy in terms of the development of a plan of motor movements that could be encoded into memory and reproduced the same way in subsequent practice.

As practice continues over the course of weeks, motor movements are reliably executed, and professional musicians shift their focus of attention from developing motor movement plans to making quite detailed decisions about interpretative elements of performance (Chaffin & Imreh, 2001). Later stages of practice reveal that musicians' starts and stops are guided by interpretive sections of the music. During this phase of practice, musicians strive to achieve the utmost nuance in phrasing and expressive detail. It is important to note that these observations do not suggest that expressive elements of playing are not considered until technical aspects of performance are acquired. As mentioned before, musicians let auditory images that include all of the expressive elements of music making guide practice from the beginning, an approach that is certainly different than the unfortunately common practice among novices of learning notes and rhythms before addressing interpretive elements of music performance.

Professional musicians use the formal structure of music to organize practice; in other words, the starts and stops that musicians make as they play coincide with musical units (Chaffin & Imreh, 1997; Miklaszewski, 1989; Nielsen, 1999a; Williamon et al., 2002). In cases where music memorization is an inherent part of learning music, as is the case with vocalists and pianists, organizing practice around the formal structure of music allows cognitive encoding that facilitates the memorization and recall of music (Chaffin & Imreh, 1997). Playing sections of music facilitates motor skill acquisition and, as most musicians would agree, playing entire sections of music is more aesthetically gratifying than playing fragments of sections.

Professional and advanced musicians are also able to shift their focus of attention between levels of the formal structure of music as they practice (Miklaszewski, 1989; Williamon et al., 2002). Over the course of preparing a piece for performance, professional and advanced pianists shift their attention between the entire piece, major sections, and from note to note. Initial stages of practice are organized around performing the piece as a whole to solidify musicians' auditory images, followed by more detailed work that occurs at the level of major sections, while also working out note-to-note problems at the level of individual measures. Practice continues in this manner, even into the final stages of practice before performance.

Nielsen (1999a) and Miklaszewski (1989) observed that playing through large sections of a piece at close to performance tempo early in the learning process is a strategy musicians employ to help solidify their image of the piece, and to help them identify where technical and interpretive problems will occur during the learning process. Playing the piece at performance tempo in early stages of practice helps musicians create necessary practice plans to accomplish learning the piece.

Advanced musicians increase the efficiency of practice by structuring practice sessions around performance goals; goals are developed to organize individual practice sessions and to achieve a beautiful and fluid performance on stage. The identification of performance goals for individual practice sessions focuses attention on specific elements of performance. Achieving predetermined goals leads to a sense of accomplishment at the end of each practice session. Those achievements contribute to the planning of future practice sessions (Chaffin et al., 2003). Even from initial stages of practice, professional musicians demonstrate the ability to anticipate where technical and interpretive problems will occur during the learning process (Chaffin & Imreh, 2001; Nielsen, 2001) and to create plans that will enable them to perform well on stage.

Professional musicians use a variety of metacognitive strategies as they practice (Chaffin & Imreh, 2001; Hallam, 2001; Nielsen, 2001, 2004); in other words, professionals monitor their practice, using many different practice strategies to accomplish effective learning. They listen carefully to the sounds they create as they play and constantly compare them to the idealized image of the piece they have in mind. When particular performance trials do not go well, professionals assess problems, evaluate the effectiveness of the strategies they are using to work out the problems, and make modifications in their approaches to solve the problems. Professional musicians also monitor their progress toward learning the pieces they are working on, and make adaptations to short-term practice goals. In short, they know how to learn independently and efficiently.

After advanced musicians identify problem areas, they focus on them in practice, using a variety of strategies to remediate problems. Advanced and professional musicians employ extensive routines of repeating targeted passages to ensure fluid technical execution (Maynard, 2006). Combined with repetition are a variety of other strategies directed at developing and solidifying an appropriate motor movement plan.

Advanced musicians choose small chunks of material to isolate during repetitive work (Chaffin & Imreh, 2001; Maynard, 2006; Miklaszewski, 1989; Nielsen, 1999a), which makes the extensive use of repetition less time consuming than it would be if larger chunks of material were chosen. 'Chunking', as this technique is often called, also increases practice efficiency by allowing attention to be focused directly on performance problems unique to the passage without distractions from surrounding material.

Short practice chunks are often played at varying tempos during practice to accommodate technical demands. Tempos for repetitions are purposefully selected, and are often not chosen in progressively increasing or decreasing order (Miklaszewski, 1989; Nielsen, 1999a). Miklaszewski's case study describes one example of purposeful tempo variation. The participants of his study first played through the piece to be learned at a near-performance tempo and identified problem areas. A small segment of the music was then chosen for isolated work. Practice tempo first decreased while motor movements for the segment were worked out. When the motor skills were reliably executed, the practice tempo was increased back to near-performance tempo. When performance of the passage at the near-performance tempo was not satisfactory, more isolated, remedial work was done at varying tempos. Once the passage was playable at the near-performance tempo, the passage was recontextualized into the section of music where it appeared before practice of a different section of music was initiated.

Another strategy used with repetition is to break apart the physical movements involved in performance and rehearse component movements separately. In the case of piano practice, professional musicians tend to alternate between playing difficult passages with one hand only and with both hands together. Organists also add pedal-separate playing to hands-together/hands-separate approaches (Nielsen, 1999a, 1999b). Wind instrumentalists may choose to finger through a passage without blowing into the instrument. Rehearsing components of physical movements separately allows musicians to direct attention to particular movements that present problems by reducing the cognitive load that typical performance presents.

Repetition of problem areas continues in the initial stages of practice until musicians feel that very short episodes of rehearsal in subsequent practice sessions will be required to maintain technical fluency (Chaffin & Imreh, 2001). Within a couple of practice sessions, there are no differences between the amount of time spent on technically difficult passages and time spent on more simple technical passages. Performance problems are addressed to the extent that performance is accurate, fluent, and consistently executed early in the learning process.

Detailed observations of the unrestricted practice of an excerpt by 17 advanced pianists (Duke, Davis, & Simmons, 2004) led to the conclusion that the organizational structure of practice is more determinative of superior playing in subsequent performance than is how much or how long one practices. The number of complete, correct trials executed during the practice session best predicted superior performance at a subsequent retention test. The pianists who best learned the passage neither spent more time practicing nor played more total trials (correct and incorrect) during practice than did other pianists who performed more poorly on the retention test. The fact that the best performing pianists took no *less* time to learn the passage than the other pianists is also notable, because it contravenes the notion that the pianists who performed best on the retention test were more highly skilled than the other pianists and thus were able to learn the passage more easily than the others.

The characteristics of the practice sessions of the three pianists who scored highest on the retention test are summarized below. Although the top scoring pianists demonstrated most or all of the behaviors listed, lower scoring pianists demonstrated only a few.

1. Playing is hands-together early in practice
2. Playing is with inflection early on; the initial conceptualization of the music is with inflection
3. Practice is thoughtful, as evidenced by silent pauses while looking at the music, singing/humming, making notes on the page, or expressing verbal "ah-ha"s
4. Errors are preempted by stopping in anticipation of mistakes
5. Errors are addressed immediately when they appear
6. The precise location and source of each error is accurately identified, rehearsed, and corrected
7. Tempo of individual performance trials is systematically varied; logically understandable changes in tempo occur between trials (slow down enough; do not speed up too much)
8. Target passages are repeated until the error is corrected and the passage is stabilized, as evidenced by the error's absence in subsequent trials
9. When tempo is changed, the first trial at the new tempo is accurate

10. After the initial learning phase errors are intermittent (no persistent errors)
11. At least 20% of all starts are complete, correct performances, though not necessarily at the target tempo

Nielsen (1999a) discusses both mental practice and distribution of practice in her analysis of a performer's practice strategies. Mental practice (e.g., imagining, without movement, the performance of a passage) prepares cognitive and physical aspects of performance away from the instrument, while limiting learner fatigue. Distributing practice over the course of a day also helps lessen physical and mental fatigue brought on by intense and continuous physical practice. Ericsson and colleagues and Nielsen have observed that advanced musicians often nap between practice sessions (Ericsson et al., 1993; Nielsen, 1999a), the effects of which are related to both recovery from fatigue and memory consolidation.

Other practice strategies mentioned less frequently in the literature include performing with a metronome, systematically altering the rhythm of difficult passages to facilitate motor skill production, studying the music in terms of formal structure, writing comments in the score (e.g., notes about the formal structure of the piece, harmonic analysis, fingering pattern reminders, and interpretive reminders), and listening to the recordings of other artists.

Musicians' verbal descriptions of their own practice strategies are not always consistent with their actual practice behaviors (Chaffin et al., 2003). Furthermore, Madsen (2004) has shown that musicians' recollections of past practice are often unreliable. Perhaps musicians' memories of their practice conflict with observations of actual practice because a degree of automaticity exists in their practice behaviors, a result of extensive practice undertaken over the course of many years. Extensive use of routines may prevent musicians from being consciously aware of exactly how they use strategies in practice.

Practice Strategies, Practice Time, and Music Performance Expertise

The ability to effectively employ cognitive (e.g., practice strategies) and metacognitive (e.g., monitoring performance and adjusting practice accordingly) skills in the practice room is a critical component of performance preparation by professional and advanced musicians. This kind of effortful and intentional practice is characteristically different from the practice of less-skilled performers (Lehmann & Ericsson, 1997). Goal-oriented practice that is consistently monitored by the performer for goal achievement has been labeled *deliberate practice*; studies in different performance domains (e.g., music, chess, sports, visual arts, sciences) have examined the role of deliberate practice in the development of performance expertise (Ericsson, 1996).

Studies of musicians show that expert-level performers began practicing deliberately during childhood, accumulating no fewer than 10 years of deliberate practice before they received professional recognition (Ericsson, 1997; Ericsson et al., 1993; Lehmann, 1997). Differences between the performance skills professional-level musicians are attributed in part to the amount of time spent in deliberate practice; in other words, professionals who engage in deliberate practice for longer periods of time eventually reach higher levels of success than do professionals who engage in fewer hours of deliberate practice (Ericsson et al., 1993; Madsen, 2004).

Extended, intense practice does not always facilitate the development of expert- and professional-level performance, however (Moore, Burland, & Davidson, 2003).

Moore et al. examined the role of deliberate practice in the musical development of children, and observed that children who engaged in intense practice from the beginning of study showed high levels of musical success initially, but did not pursue music performance as a career. The children who did become adult professional musicians gradually increased the amount of practice they engaged in over the course of many years rather than practicing intensely for extended periods of time from the beginning of study. These data suggest that intense practicing from the very beginning of music study may dampen interest in pursuing high levels of music performance skill in the long-term.

Practice Strategy Observations in the Practice of Developing Musicians

Research in music education has sought to determine how practice strategies can be effectively implemented in the practice of developing musicians. In these investigations, practice strategies of professional and advanced musicians have been taught to developing musicians to examine their effectiveness.

Structured practice improves performance more so than unstructured or free practice (Barry, 1992; Puopolo, 1971), particularly among developing musicians. It seems clear that beginning instrumentalists must learn *how* to practice with skill development in mind. Teachers must not only introduce practice strategies through explanation, but must practice the implementation of effective practice procedures with their students.

Physical practice improves music performance to a greater extent than does studying scores while listening to recordings (Lim & Lippman, 1991) or engaging in mental practice (Coffman, 1990; Ross, 1985) in the absence of physical practice. This is unsurprising, as neither cognitive preparation nor mental practice fully engage the movements that are necessary for the refinement of motor movement plans.

Combining physical and mental practice optimizes cognitive coding and engages attention and arousal (Theiler & Lippman, 1995), but tests of combined physical and mental practice in music have produced inconsistent results. Rubin-Rabson (1941), for example, observed that combining physical and mental practice facilitated performance more than physical practice alone. Coffman (1990) and Ross (1985) observed that physical practice alone and combined physical/mental practice improved performance similarly, and the combination of physical/mental practice improved performance significantly more than mental practice alone.

Listening to recorded models during physical practice improves performance more than physical practice only (Henley, 2001; Hewitt, 2001; Lim & Lippman, 1991; Puopolo, 1971; Rosenthal, 1984; Rosenthal, Wilson, Evans, & Greenwalt, 1988; Theiler & Lippman, 1995). Listening to recorded models provides an auditory image of the practice goal and thus increases the effectiveness of physical practice. Combining recorded model listening, mental practice, and physical practice facilitated the memorization of vocal and guitar music (Theiler & Lippman, 1995) to a greater extent than combined physical/mental practice and physical practice alone. Listening to a recording of a piece while studying its score also improves performance (Lim & Lippman, 1991). Rosenthal et al. (1998) observed that listening to a model in the absence of physical practice and physical practice without a recorded model both enhanced performance to the same extent, though in this experiment, practice time was limited to three minutes. Hewitt (2001) observed that having young students listen to recordings of their own playing improved subsequent performance only if students also listened to a recorded model. This result supports the notion that recorded models provide, especially for inexperienced musicians, a clear performance goal that helps guide decision making during practice.

Puopolo (1971) observed that beginning instrumentalists demonstrated improved performance after practicing with a recording that provided aural models of practice material, gave cues about elements of performance (e.g., fingerings, accidentals), asked students to evaluate their performances, and required several repetitions of material. The beneficial effects of listening to recorded models that also guide musicians' practice behaviors are mediated by age. Rosenthal (1984) observed that more experienced musicians (college level) did not benefit as much from a listening to a recorded model that also guided practice as they did from listening to a recorded model that did not include a guide for practice behavior. These results suggest that experience and skill level mediate the effect of guided practice; college-level musicians who have completed years of training are more equipped to effectively guide their own practice than are less experienced musicians.

Observations made in some of the first documented studies of developing musicians' practice are consistent with information gathered in the case studies of advanced and professional instrumentalists. Brown (1928) observed that both practicing complete sections of music (whole practice) and alternating between practicing complete sections and isolating problem areas (combination of whole/part practice) was more effective in improving performance than was breaking up sections into parts without playing complete sections (part practice). In contrast, Rubin-Rabson (1940b) did not observe differences between whole- and part-practice. Brown and Rubin-Rabson also reported different results for hands-together and hands-separate practice; Brown (1933) noted that hands-together practice was more effective than hands-separate practice, whereas Rubin-Rabson (1939) observed no differences between the two strategies.

Differences between the results of these studies may be attributed to differences in their methodologies and their dependent measures.

Spacing practice over time (i.e., distributed practice) was more shown to be effective in improving performance than practicing for the same amount of time in one session (i.e., massed practice) (Rubin-Rabson, 1940a). This landmark study was the first comparison of massed and distributed practice in the context of music. Adult musicians with extensive piano training were given 30 trials to learn a passage on the piano that required coordinated performance of both hands; they either completed 30 trials in one session, or completed 15 trials in each of two sessions, spaced by 1 hour or by 24 hours. A 2-week delayed retest showed that pianists whose practice was distributed across two sessions were able to perform the passage without error in fewer trials than did pianists who engaged in massed practice. Although there were no significant differences between the 1- and 24-hour distributed practice groups, the largest performance differences were observed between the 24-hour distributed practice group and the massed practice group.

One strategy found to benefit learning with advanced and professional pianists was found to be ineffective when employed by novice musicians. Henley (2001) observed that alternating between slow and fast tempos during practice did not improve performance more than practicing with a gradually increasing tempo, nor did it improve performance more than practicing at performance tempo only.

Even though effective practice strategies have been identified in research, their implementation in the practice of most developing musicians has yet to be fully described (Pitts, Davidson, & McPherson, 2000). The strategy that occurs most often in the practice of developing musicians is repetition; however, repetitions typically do not thoroughly address error correction. If error correction is attempted, most developing musicians briefly implement ineffective strategies to correct errors and move on before problems are solved (McPherson & Renwick, 2001). In other words, beginning instrumentalists tend to play through music a couple of times, paying little attention to errors and overall performance quality, rather than setting goals for each practice session and monitoring performance to ensure that goals are achieved.

In a study of practice by artist-teachers and their students, Maynard (2006) observed that artist-teachers, graduate students, and advanced undergraduates selected over twice as many targets for isolated practice than did beginning undergraduates. The least advanced undergraduate group performed almost half the number of repetitions in practice than did the more advanced groups. Differences in practice habits exist between more-skilled and less-skilled performers, even at the collegiate level.

The demonstration of cognitive and metacognitive practice strategies early in instrumental study is a reliable predictor of musical success (McPherson & Renwick, 2001). A small percentage of developing musicians use cognitive and metacognitive practice strategies, albeit in a manner less sophisticated than that observed among more experienced musicians. Hallam (2001) observed that young instrumentalists who use practice strategies effectively are also able to identify technically demanding passages in score study and aurally identify errors. Differences between more successful and less successful instrumentalists become evident quite early; they are observable even in children as young as six years of age and by instrumentalists' second year of study (Sloboda, Davidson, Howe, & Moore, 1996).

Children must be taught to be self-motivated, independent learners who enjoy playing their instrument. Playing beautifully is motivating, but the work required to develop the motor, cognitive, and meta-cognitive skills necessary to play beautifully is often too arduous for developing musicians who have not learned how to engage in effective practice techniques independently. However, when students are free to exercise choices in practice they are more likely to enjoy it, persevere in the face of problems, and persist in the activity (Renwick & McPherson, 2002). Renwick and McPherson observed, for example, a young instrumentalist engaged in advanced practice strategy behavior (e.g., humming, fingering silently, studying the music, practicing larger sections, persisting for longer periods of time to correct errors) when practicing a piece that was self-selected. This practice behavior differed markedly from the practice behavior she engaged in when she practiced teacher-selected repertoire.

Young instrumentalists reported enjoying practice more when repetitions of difficult material included varying performance elements (e.g., different rhythms, different tempos, changing articulation) than when repetitions were performed identically (da Costa, 1999). Sloboda et al. (1996) observed that students were more likely to succeed in music performance if they supplemented formal practice (e.g., scales, etudes, teacher-assigned repertoire) with informal practice (e.g., improvisation, playing by ear).

Practice strategy instruction is not consistently observed in private lesson studio teaching (Barry & McArthur, 1994), and what teachers think they are teaching their students about practice is not always evident in students' practice room behavior (Kostka, 2002). Kostka's survey of college-level private studio instructors reported that teachers had the expectation that students followed a specific practice routine, but more than half of their students indicated that they did not do so. Nearly all teachers in the survey stated that they discussed practice strategies in students' lessons, but well over half of the students reported that practice strategies were not discussed in their lessons. Perhaps the least surprising observation was that teachers expected that more time was spent in practice than was reported by students.

Music Practice Research Conclusions

Musicians of all ages and ability levels engage in physical practice to improve performance. The most important findings from the research described above are that professional and advanced musicians engage in goal-oriented, deliberate practice behavior, employing metacognitive skills to monitor their progress over time. In contrast, developing musicians typically do not practice effectively and do not carefully monitor their progress.

Studies of music practice to date have not examined all that musicians do while practicing, and they offer only limited information about the optimal applications of practice strategies. Some strategies, like Rubin-Rabson's 1940 comparisons of massed and distributed practice in music memorization, have received little attention in music learning research. The effectiveness of systematically varying practice content also requires further study in the context of music performance.

Distributed practice and variability of practice have received considerably more attention in contexts other than those typically discussed in music research. Many of the investigations of motor skill learning and procedural memory test simpler motor skills than those involved in music performance, but the principles of human learning and memory that have been described in these investigations offer a wealth of information about the cognitive and physical processes that underlie performance improvements of motor skills in general.

CURRENT THEORIES OF MOTOR SKILL LEARNING AND MEMORY

Researchers have published a number of studies that investigate how motor skill learning and memory are affected by the structure of practice. Much of this work was designed to test the schema theory of motor learning (Schmidt, 1975); schema theory addresses how motor skills are represented in memory and how the degree of variation in practice influences cognitive and behavioral components of learning. The impact of schema theory remains robust 31 years after its introduction. Schmidt's schema theory publication has spawned decades of research designed to test the principles of human motor learning that it described (C. H. Shea & Wulf, 2005).

A major premise of schema theory is that when a sequence of motor movements is executed repeatedly, the brain creates a *motor program* that is a cognitive representation of those coordinated movements (Schmidt & Lee, 1999). A motor program represents the fixed relationships between individual movement segments that comprise a motor skill. In other words, motor programs are invariant structural patterns of proportional relationships among movements. Invariant patterns of proportional relationships are somewhat analogous to note values that comprise the rhythm of a melody. A given melody may be performed at various tempos that require the overall rhythmic structure to be performed faster or slower, but the relationships between notes in the melody stay the same. When evoked by sensory information in the environment, a motor program generates production of the coordinated movement pattern it represents (e.g., a performer sees a cue from a conductor that initiates recall of a motor program that produces sound from the instrument).

Motor programs are not always executed under the same performance parameters. The term *generalized motor program* (Schmidt, 1975), or GMP, refers to motor programs that can be executed under different performance parameters (e.g., performing the rhythm of a melody at various tempos). In other words, the proportional relationships between the movements (e.g., rhythm) do not change, but the conditions under which they are executed (e.g., tempo) vary.

Cognitive information about movements and the results of movements are processed as a GMP is being learned (Schmidt & Lee, 1999). First, proprioceptive information that precedes movements is processed (e.g., how fingers are positioned over the keys of a piano). Second, information about unique performance parameters applied to GMPs is stored (e.g., performing the rhythm of a melody at M.M. = 92). Learners then evaluate the results of movements after GMP execution (e.g., was the rhythm performed accurately at this tempo?), and they process sensory information about how it felt to execute the GMP under specific performance parameters (e.g., evaluating whether a particular fingering pattern used to execute a rhythm is awkward or comfortable at a given tempo).

As learners continue to execute a GMP under varying performance parameters, they begin to form relationships between the GMP, the parameters under which the GMP is executed, and the results of their attempts to adjust their movements to accommodate various performance parameters while maintaining GMP structure. The cognitive representation of these relationships comprises a *recall schema* (Schmidt, 1975). Recall schemas may be thought of as a set of rules that allow a GMP to be executed in different contexts; the relationships between movements stay constant while the actual parameter value for each component movement of the GMP changes to accommodate the requirements of each situation.

In the motor learning literature, the extent to which skills are learned is typically assessed in two measures: retention tests and transfer tests. Retention tests are performed after varying time intervals following practice (e.g., minutes, days, weeks). Retention tests usually comprise a limited number of performance trials that are identical to acquisition trials. Transfer tests are usually conducted after retention tests and typically involve performing a number of trials that are slightly altered versions of acquisition trials (e.g., playing the practiced rhythm of a melody at a previously unpracticed tempo). Retention tests provide information about the integrity of the memory formed for new skills as a result of practice. Transfer tests measure the extent to which new skills are successfully applied to new contexts. Assessing learners' ability to recall and transfer skills is a universally accepted measure of learning (Simon & Bjork, 2002).

Retention and transfer tests demonstrate that practice that facilitates GMP learning is different from practice that facilitates development of the recall schema for a GMP. A GMP is most efficiently learned under practice conditions that promote stability in movement execution (i.e., parameters for movement execution stay the same between performance trials; see Giuffrida, Shea, & Fairbrother, 2002; Lai & Shea, 1998; Lai, Shea, Wulf, & Wright, 2000; C. H. Shea, Lai, Wright, Immink, & Black, 2001). This trial-to-trial consistency allows attention to be directed at the fundamental structure of the movement pattern, which strengthens the formation of the GMP. Constant practice (identical repetitions of one task throughout practice) and blocked practice (completing all performance trials under one set of parameters before beginning practice under a different set of parameters) are the most stable kinds of practice identified in motor learning literature.

Although stable practice facilitates GMP learning, it does not enhance the ability to execute movement patterns in different contexts (Giuffrida et al., 2002; Lai et al., 2000; C. H. Shea et al., 2001; Wright & Shea, 2001). Practicing skills on a variable schedule, where parameters for movement execution change between performance trials, is necessary for the development of a recall schema that facilitates executing a GMP in new contexts. This trial-to-trial inconsistency requires attention to be focused more on negotiating parameter changes and less on learning the underlying structure of the movement pattern (GMP). The more practice is varied, the more experience learners have executing GMPs in changing contexts; these varied experiences enhance recall schema development. Serial practice (performance parameters for each trial vary in a systematic way that is repeated throughout practice) and random practice (performance parameters for each trial vary quasi-randomly throughout practice) are the kinds of variable practice typically described in the motor learning literature.

The Effects of Stable and Variable Practice on Motor Skill Learning and Memory

Surprisingly, many studies show that learners who engage in variable practice during the acquisition phase of learning demonstrate better retention and/or transfer than do learners who engage in stable practice (Albaret & Thon, 1998; Li & Wright, 2000; Pollock & Lee, 1997; C. H. Shea, Kohl, & Indermill, 1990; C. H. Shea et al., 2001; Simon & Bjork, 2001; Tsutsui, Lee, & Hodges, 1998; Young, Cohen, & Husak, 1993). The observation that variable practice enhances transfer test performance seems intuitive; variable practice offers learners frequent experiences executing movements in changing contexts, whereas stable practice offers no such experience (constant practice) or quite limited experience (blocked practice) with varied parameters.

One unsurprising effect of including variability in practice is that more errors are made during the acquisition phase of learning than are typically observed when learners are engaged in stable practice (Giuffrida et al., 2002; Li & Wright, 2000; Pollock & Lee, 1997; C. H. Shea et al., 1990; C. H. Shea et al., 2001; Simon & Bjork, 2001; Tsutsui et al., 1998; Young et al., 1993). When performance parameters change with each trial, learners are more likely to make errors than they are when parameters stay the same between trials. It seems in some ways counterintuitive that learners engaged in variable practice make more errors during the acquisition phase of learning than stable practice learners but demonstrate better performance on retention tests; more errorful practice yields better learning.

Variable practice enhances learning more than stable practice because it engages the memory system in more complicated ways, requiring more information processing and encoding as learners negotiate changing parameters (Albaret & Thon, 1998; Immink & Wright, 1998, 2001; C. H. Shea et al., 1990; Wulf & Shea, 2002). The benefits of this elaborate cognitive processing are described by two competing ideas, namely, the Reconstruction and Elaboration Hypotheses (Schmidt & Lee, 1999; Young et al., 1993). The Reconstruction Hypothesis proposes that learners create a new action plan for each trial they encounter. Previously used action plans are not engaged when learners develop action plans for new trials performed under different parameters (Giuffrida et al., 2002; Immink & Wright, 1998; Schmidt & Lee, 1999). The high level of cognitive processing involved in the trial-to-trial reconstruction of action plans enhances memories for practiced tasks. The Elaboration Hypothesis proposes that information about each performance trial is stored in working memory. Continuous comparisons between new trials and previously experienced trials require high levels of cognitive processing that lead to distinct and elaborate memories. Similar cognitive demands are not experienced with stable practice schedules. Executing movements the same way from trial to trial allows a degree of cognitive and motor automaticity to develop over time, resulting in less elaborate memories for new skills.

Motor learning research that examines the effects of including variability in practice has been guided by two competing theories. The *variability of practice hypothesis*, proposed by Schmidt (1975), describes the effects of varying performance parameters on motor learning (e.g., performing the same movement at different speeds). The second hypothesis, the *contextual interference effect* (J. B. Shea & Morgan, 1979), discusses the effect of executing different movement sequences (GMPs) of the same movement type on learning (e.g., performing slightly different movements at the same speed). The contextual interference effect suggests that varying the GMP executed in consecutive performance trials creates cognitive interference for learners as relationships between movements are changed from trial to trial. Much has been made of the difference between the variability of practice hypothesis and the contextual interference effect in motor learning literature; however, there are some generalities to draw from both ideas. Both kinds of variation (negotiating changing parameters or negotiating different GMPs from trial to trial) interfere with learners' ability to execute movements consistently. The interference created by GMP and/or parameter variation increases the cognitive processing load imposed on learners during the acquisition phase of learning, thereby enhancing the memory formed for new skills. (In the investigation reported in this dissertation, practice variation is included by learners' negotiation of performance parameter changes as described by the variability of practice hypothesis.)

Complexity in Motor Skill Learning Mediates Practice Schedule Benefits

Motor learning research consistently demonstrates that variable practice enhances simple motor skill learning; however, research that explores complex skill learning demonstrates that the benefits of variable practice are mediated by task complexity and sophistication of learners (Guadagnoli & Lee, 2004; Wulf & Shea, 2002). In complex skill learning, the extent to which variable practice enhances learning is inversely related to the degree of task complexity (Albaret & Thon, 1998). In other words, as tasks increase in difficulty, benefits of variable practice decrease. Complex motor skill execution requires more cognitive effort than simple motor skill execution, and variable practice requires more cognitive processing than stable practice. The combination of increasing cognitive demands both in task difficulty and in practice schedule often overloads cognitive processing of naïve learners. The interaction between task complexity and practice variability was clearly demonstrated by Albaret and Thon; variable practice enhanced learners' drawing performance when tasks were relatively simple (drawings that consisted of 2 or 3 segments), but did not enhance learning of the more complex task (drawings that consisted of 4 segments).

The extent to which variable practice enhances learning is positively related to sophistication of learners. In other words, as learners become more sophisticated in terms of the target skill, benefits of variable practice increase. More sophisticated learners are able to acquire more complex tasks than are less sophisticated learners. Jarus and Gutman (2001), for example, observed children learning a simple and a complex throwing task; stable practice facilitated learning of both tasks, whereas variable practice only enhanced learning of the simple task. Children could not accommodate the cognitive demands required to execute a complex task under a variable practice schedule. With increasing age typically comes increasing motor coordination and control. Jarus and Gutman also observed that college-aged learners who engaged in variable practice of a dart-throwing task demonstrated a greater degree of learning than did those who engaged in stable practice.

The relationship between practice variability and learner sophistication also varies with learners' pre-existing levels of motor coordination and control. Hebert et al. (1996) separated college students enrolled in a beginning tennis course into low- and high-skilled groups based on pre-test scores. Stable practice enhanced performance of low-skilled beginners more than variable practice, and there were no differences between the extent to which stable and variable practice enhanced learning of high-skilled beginners. Surprisingly, Hebert et al. also observed that variable practice did not produce more error in the acquisition phase of learning than did stable practice.

Learners demonstrate varying levels of ability when acquiring new skills and consequently respond to skill complexity uniquely; in general, learning is optimized when the difficulty of a given task matches the ability of a learner and when the degree of variability in practice is modified according to that relationship. In one such example of optimized learning, collegiate-level baseball players clearly demonstrated that variable practice enhances performance of highly complex motor skills when learners are highly competent with the task (Hall, Domingues, & Cavazos, 1994). Skilled baseball players completed two sessions of additional batting practice every week for six weeks. Athletes who engaged in variable practice outperformed athletes who engaged in stable practice in both retention and transfer tests, which demonstrates that variable practice enhances highly complex skills performed by quite sophisticated learners.

There are inconsistencies in the motor learning literature that are currently attributed to the complicated nature of matching learners' ability with the appropriate degree of task complexity and to the fact that procedures used to study practice variability are not identical from one experiment to another (for a review, see Wulf & Shea, 2002). Thus, beneficial effects of practice variability on complex motor skill performance have been found in studies of baseball (Hall et al., 1994), racket sports (Green, Whitehead, &

Sugden, 1995), aiming tasks (Pollock & Lee, 1997), throwing tasks (Wulf, 1991), and computer games (Shewokis, 1997). No beneficial effects were found in studies of racket sports (Hebert, Landin, & Solmon, 1996), basketball (Shoenfelt, Snyder, Maue, McDowell, & Woolard, 2002), computer games (Shewokis, 2003), and throwing tasks (Jarus & Gutman, 2001).

In these and the other studies described above, learners engaged in either stable or variable practice; several authors have proposed that learning may benefit most from a combination of stable and variable practice (Lai et al., 2000; Lee & Wishart, 2005; C. H. Shea et al., 1990; Wulf & Shea, 2002). In the earliest stages of acquiring a new task, stable practice schedules, where movements remain the same from trial to trial, do not overload learners with the cognitive processing demands associated with variable practice. Once movements are reliably executed with stable practice, learners are no longer challenged by the lower cognitive demands of stable practice. Engaging in variable practice after movements are reliably executed increases cognitive demands at a point in the learning process when learners benefit from negotiating parameter and/or GMP changes.

Knowledge of Results Influences Learning

Providing learners with knowledge of the results of their movements influences learning under both stable and variable practice schedules. It is important to note that *knowledge of results* (KR) is distinguishable from *knowledge of performance* (KP), which provides learners with information regarding the nature of their movements rather than focusing only on the outcome of the movement (KR) (e.g., whether a ball hit its target). Learners who immediately receive information about the outcome of their movements

(KR) after every performance trial are not required to engage in self-assessment. Delaying the presentation of KR and/or reducing KR frequency allows learners to develop their own mechanisms for error detection and self-correction, which increases the amount of cognitive involvement required during practice (Swinnen, Schmidt, Nicholson, & Shapiro, 1990).

The optimal amount of KR for a given learner depends on the learner’s sophistication, the complexity of the task, and the amount of variability associated with practice (Guadagnoli & Lee, 2004). More skilled learners require less immediate and less frequent feedback than do less skilled learners, because more skilled learners benefit from increased cognitive demands that are engaged through self-evaluation and self-correction. With complex tasks, more immediate or more frequent KR facilitates learning, whereas delayed or less frequent KR is more beneficial in learning simple tasks; again, learning is optimized when cognitive demands required by task complexity and KR frequency are balanced.

To optimize learning, a balance must be achieved between cognitive demands created by practice schedule conditions and KR frequency (del Rey & Shewokis, 1993). Del Rey and Shewokis observed that performance under variable practice schedules was enhanced by less frequent KR (given after groups of ten trials), whereas performance under stable practice schedules was enhanced by constant KR. Learners who engage in variable practice are overloaded by processing KR after every trial; reducing KR frequency under variable practice schedules makes movements more stable (Lai & Shea, 1998). Bandwidth KR, providing qualitative feedback that indicates success within a range around the performance goal, also stabilizes movements in variable practice (Lai & Shea, 1998; Lai et al., 2000) by directing attention toward fluid movement execution rather than at processing detailed feedback for each trial.

Immediate and constant KR enhance performance during the acquisition phase of learning more than does reduced KR (Anderson, Magill, & Sekiya, 2001; Schmidt, Young, Swinnen, & Shapiro, 1989); however, once movements are stabilized, gradually reducing KR across practice trials enhances learning (Guadagnoli, Dornier, & Tandy, 1996; Winstein & Schmidt, 1990). As learners gain experience with movements, gradually fading KR allows them to develop self-correction and assessment abilities that enhance learning. If learners are provided feedback about their movements as they happen (i.e., feedback is concurrent with movement execution), learning during acquisition is impaired (Schmidt & Wulf, 1997); perhaps attending to concurrent feedback focuses attention on modifying movement segments as they happen and diverts attention away from fluid execution of the movement as a whole.

Distributed Practice in Motor Learning Research

It has been demonstrated repeatedly that learners whose practice trials are distributed across multiple sessions over the course of two or more days perform better than do learners who practice the same number of trials in one session (massed practice) (Dail & Christina, 2004; Donovan & Radosevich, 1999; Lee & Genovese, 1988; Lee & Wishart, 2005; C. H. Shea, Lai, Black, & Park, 2000). The benefits of distributed practice over massed practice with continuous motor tasks (i.e., balancing tasks and ski-simulator tasks) have been consistently observed (for meta-analyses, see Donovan & Radosevich, 1999; Lee & Genovese, 1988). The superiority of distributed practice over massed practice (i.e., tasks that have a clear beginning and end, as with sequences of key presses and golf putting) has been less consistently observed in learning discrete motor tasks (Donovan & Radosevich, 1999; Lee & Wishart, 2005).

No well-defined theory exists in the motor learning literature that explains why distributed practice enhances learning more than massed practice, although several researchers have suggested that learning is enhanced by biological processes that occur during rest intervals between practice sessions (Dail & Christina, 2004; C. H. Shea et al., 2000; Shewokis, 2003). These biological processes, termed *memory consolidation*, are neurophysical changes that occur in the brain during rest intervals between practice sessions (memory consolidation will be discussed in further detail in the next section of this review); these changes lead to enhancements in skill performance.

Donovan & Radosevich (1999) showed that the extent to which distributed practice enhances learning is mediated by task complexity. In a meta-analysis of 63 experiments that studied the effects of distributed practice on learning, they found that distributed practice enhances learning in tasks of lower complexity to a greater extent than that observed with tasks of higher complexity. The authors categorized task complexity in each experiment into one of four levels determined by the combination of physical requirements, mental requirements, and overall complexity. The four levels of task complexity all had having high levels of physical requirements, but varied in mental requirements and overall complexity. Tasks identified as low in mental requirements and low or average in overall complexity included motor skills such as typing, tossing a ball, playing video games, and learning mazes. Skills identified as low in mental requirements and high in overall complexity included gymnastics skills and balancing. Motor skills considered high in mental requirements and overall complexity included music performance and airplane control simulation.

The majority of extant studies have examined distributed practice effects using tasks identified as having low/average mental requirements and low overall complexity (according to Donovan and Radosovich's classification scheme). Most of these studies show that distributed practice enhances learning more than massed practice. Two recent studies have clearly demonstrated distributed practice benefits using a balance task (C. H. Shea et al., 2000) and golf putting (Dail & Christina, 2004), both of which are high in overall complexity. Simmons and Duke (2006) and Rubin-Rabson (1940a) are the only studies I found that observed distributed practice enhancements using music performance tasks, which are high in mental requirements *and* overall complexity.

Donovan and Radosevich (1999) also found that optimal rest interval durations exists for tasks of different complexities. Simpler tasks benefit from shorter rest intervals between practice sessions, whereas more complex tasks benefit from longer rest intervals. These authors suggest that the benefits of distributed practice may be mediated by the learners' initial levels of skill on the task to be practiced; that question remains unexplored in existing literature.

Motor Learning Research Summary

As a learner begins to practice a new motor skill, a neural representation of that skill, a motor program, is formed in the brain. This motor program represents the fixed relationships between movements that comprise the skill. *Generalized motor programs* (GMPs) are representations that allow invariantly structured motor programs to be executed under varying performance parameters. Varied practice generates a set of rules, a *recall schema,* that facilitates the execution of the learned skill in novel contexts while retaining the integrity of the governing GMP.

Practice that facilitates GMP learning is different from practice that enhances the development of a recall schema. GMP learning is best accomplished when practice is stable (i.e., skills are executed the same way from trial to trial). Recall schema development is most enhanced by variable practice (i.e., skills are executed under performance parameters that change from trial to trial). Cognitive demands placed on learners during practice increase as variability from trial to trial increases.

A large body of motor learning research done with relatively simple motor skills demonstrates that variable practice leads to better retention than does stable practice. Researchers propose that the beneficial effect of variable practice is explained by the heightened levels of cognitive engagement required of learners who execute movements under performance parameters that change from trial to trial.

Research done with more complex motor skills shows that the benefits of variable practice are mediated by the complexity of the task to be learned and the skill level of the learner. Learning is optimized when the difficulty of a given task matches the ability of a given learner and when the degree of variability in practice is modified according to that relationship.

Relevance of Motor Learning Research to This Study

Our current understanding of how people learn motor skills is certainly incomplete. The complexity of the interactions among learner sophistication, practice variability, and practice distribution makes it difficult to obtain reliable findings that are generalizable among skills, learners, and contexts. All combinations of these variables have not been studied thoroughly; in particular, little is known about interactions between practice variability, practice distribution, and learners who have considerable task-related knowledge.

Our understanding of the mechanisms by which distributed practice enhances memory formation and performance is also lacking, particularly in relation to the neurocognitive changes that underlie behavioral improvements. Describing the neural processes that underlie memory formation has long been the focus of research in psychology and neuroscience (McGaugh, 2000). The results of this body of work describe neurological principles that obtain in massed and distributed practice contexts.

Human Learning From the Neural Perspective

It has long been known that the brain is modified through experience, and although the mechanisms of neural plasticity have been more clearly characterized in recent years, the development and modification of the neural representations of complex behavior are not well understood. Some aspects of neural function are known; for example, specific locations in the cerebral cortex—the outermost layer of the brain—are related to specific parts of the human body both for incoming sensory information (afferent stimuli) and outgoing motor signals (efferent stimuli). Imaging studies have allowed researchers to identify areas of the brain that become active when we engage in specific kinds of activity.

What is less clearly understood is how brain function is altered when learners actively engage in processing new sensory stimuli and when they acquire new motor skills. For more than a century, researchers have tried to identify how memories for experiences are formed and stored. Now widely accepted is the idea that forming memories for new skills requires structural and functional reorganization in the brain (Walker & Stickgold, 2006). The remainder of this review focuses on what is known about human learning and memory in the motor skill domain.

Motor Skill Acquisition Elicits Unique Patterns of Brain Activation

As all human beings have experienced, the performance of novel movement sequences improves rapidly at first, after which the rates of improvement in accuracy and speed decrease and eventually level off (Fischer, Hallschmid, Elsner, & Born, 2002; Karni et al., 1998; Korman, Raz, Flash, & Karni, 2003; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002). Rapid, within-session improvements in performance comprise the *fast learning* stage of motor skill acquisition (Karni et al., 1998).

As movement sequences are repeated during an initial practice session, the neural patterns that direct the movements change (Floyer-Lea & Matthews, 2005). The primary motor cortex (M1) is activated when a learner begins to practice a new finger sequence. As repetitions of the sequence continue, activity in M1 first decreases, but later in the same practice session, sequence-specific neural activity increases (Karni et al., 1995). This sequence-specific activation is characterized by the "unmasking" of previously existing neural connections. In essence, connected neurons that are not likely to fire together before practice begins, fire together easily as the result of continued activation as a sequence is repeated during practice (Karni et al., 1998; Kleim et al., 2004; Walker, 2005). During this fast learning stage, observable improvements in motor skill performance, in terms of speed, accuracy, and evenness, are outward manifestations of neurophysical changes in the cortex. The refined pattern of neural activation that emerges by the end of the fast learning stage comprises a neural representation of the newly acquired motor skill (Walker, 2005).

It seems commonly held that the act of learning a motor skill (e.g., improving performance) is synonymous with physical activity and conscious attention—that as learners practice, repeating skills to increase strength, fluency, automaticity, flexibility, accuracy, and speed (Maynard, 2006), the brain undergoes physical changes as increasingly refined neural pathways are formed. Less obvious is the fact that learning continues *after* the cessation of practice, even when learners devote their attention and efforts elsewhere. The *slow learning* phase begins as the brain continues "off-line" processing of initially fragile neural representations for newly acquired motor skills without any conscious effort on the part of the learner.

Neural Representations for Motor Skills are Modified Subsequent to Practice

Consolidation is the off-line process through which motor skills and other procedural memories are encoded and refined, resulting in their resistance to interference and forgetting (McGaugh, 2000; Walker, 2005; Walker & Stickgold, 2004). Although the process of consolidation has yet to be fully characterized, it is currently described as a time-dependent process that begins during physical practice and continues after practice has ended (Luft & Buitrago, 2005). If the consolidation process continues unabated for four to six hours after the cessation of practice, new motor memories become resistant to interference, thus maintaining performance levels achieved during practice (Walker, Brakefield, Seidman et al., 2003).

If interfering stimuli (e.g., the practice of new tasks that are similar, but not identical, to the tasks learned during training) are introduced within four to six hours of training, the consolidation process may be disrupted and learners may show decrements in performance during subsequent testing (Brashers-Krug, Shadmehr, & Bizzi, 1996; Shadmehr & Brashers-Krug, 1997; Walker, Brakefield, Hobson, & Stickgold, 2003). Memory consolidation may also be interfered with if learners experience cerebral trauma (McGaugh, 2000), if the electrical activity of specific brain areas is altered (Muellbacher et al., 2002; Robertson, Press, & Pascual-Leone, 2005), or if learners take drugs that alter neural function (Donchin, Sawaki, Madupu, Cohen, & Shadmehr, 2002).

A sufficient amount of practice during acquisition is required to trigger consolidation processes; learners must achieve a degree of performance success and complete a sufficient number of repetitions in practice for memories to be encoded and refined (Hauptmann & Karni, 2002; Hauptmann, Reinhart, Brandt, & Karni, 2005; Karni et al., 1998; Walker, 2005). The initial, rapid improvements often observed during the acquisition phase of learning must level off before practice ends in order to trigger consolidation processes. At the point when performance improvements become more incremental, a relatively clear neural representation of the skill has formed; that representation is then "tagged" for processing that continues after practice has ended (Walker, 2005).

Consolidation processes that begin subsequent to practice occur in two distinct phases (Walker, 2005). *Consolidation-based stabilization* begins at or near the end of skill acquisition and is completed four to six hours later. During this time, learners are awake and engaged in other activities. Studies of motor skill learning in humans have shown that levels of performance accuracy and speed attained by the end of an initial training session are sustained during subsequent time awake (Hotermans, Peigneux, Maertens de Noordhout, Moonen, & Maquet, 2006; Robertson, Pascual-Leone, & Miall, 2004; Robertson, Pascual-Leone, & Press, 2004; Walker, Brakefield, Hobson et al., 2003; Walker et al., 2002; Walker, Brakefield, Seidman et al., 2003). Two studies reported enhancements in performance speed following consolidation that occurred during time awake (Fischer et al., 2002; Walker, Brakefield, Seidman et al., 2003); however, neither study reported similar observations in performance accuracy. These inconsistencies in observations of speed enhancements are not discussed in the literature. Current theory proposes that wake-based consolidation is characterized by intermittent occurrences of task-related neural activity that persist beyond practice, by early protein synthesis in the brain, and by the potentiation of freshly unmasked neural connections (Peigneux et al., 2006).

Consolidation-based enhancement begins sometime after the onset of consolidation-based stabilization, and, in most procedural skills, is dependent on the biological processes of sleep. During the enhancement phase of consolidation, neural representations are modified in the absence of additional practice in ways that facilitate improvement in skill execution; in other words, sleep enhances motor skill performance. Processes of consolidation that include sleep have been shown to significantly enhance a variety of procedural skills, including motor skills (Brashers-Krug et al., 1996; Duke & Davis, 2006; Fischer et al., 2002; Fischer, Nitschke, Melchert, Erdmann, & Born, 2005; Hotermans et al., 2006; Karni et al., 1998; Korman et al., 2003; Kuriyama, Stickgold, & Walker, 2004; Maquet, Laureys et al., 2003; Mednick, Nakayama, & Stickgold, 2003; Robertson et al., 2005; Vertes & Eastman, 2000; Walker, Brakefield, Hobson et al., 2003; Walker, Brakefield, Seidman et al., 2003), serial reaction time (Robertson, Pascual-Leone, & Press, 2004), auditory discrimination skills (Atienza & Cantero, 2001; Atienza, Cantero, & Dominguez-Marin, 2002; Atienza, Cantero, & Stickgold, 2004), visual discrimination skills (Karni, Tanne, Rubenstien, & Askenasy, 1994; Maquet, Schwartz, Passingham, & Frith, 2003; Mednick et al., 2002; Mednick et al., 2003; Stickgold, James, & Hobson, 2000), and verbal discrimination skills (Fenn, Nusbaum, & Margoliash, 2003). The results of this research reveal performance enhancements subsequent to sleep, but no enhancements following consolidation intervals that do not include sleep (Fischer et al., 2002; Walker, Brakefield, Hobson et al., 2003). Careful controls have excluded the possibility of performance differences due to circadian influences (i.e., the times of day of training and retesting) (Fischer et al., 2002).

Current theory suggests that processes that occur during sleep are responsible for modifying neural networks in ways that enhance performance following sleep (Benington & Frank, 2003). Some neural networks active during the acquisition phase of learning are no longer necessary for optimal performance of a newly learned skill at subsequent retest. During sleep, those neural networks are disengaged (Fischer et al., 2005), yielding a modified and more refined neural representation of the skill. Sleep studies have demonstrated that patterns of brain activity active during new task learning are again active during sleep, as if the brain is "replaying" significant events of the day (Walker & Stickgold, 2006). More invasive work done with cats has clearly demonstrated that modifications of neural connections occur during sleep (Frank, Issa, & Stryker, 2001). Sleep-based consolidation allows motor skills to be performed more quickly, accurately, and more automatically as a result of a large-scale reorganization of neural representations across several brain areas (Walker & Stickgold, 2006).

It has long been known that there are two broad classifications of human sleep, REM (rapid eye movement) sleep and NREM (non-rapid eye movement) sleep, the latter of which is separated into four distinct stages. Each type and stage of sleep is characterized by distinct patterns of electrical and neurochemical activity in the brain. As humans sleep, they cycle through these types of sleep approximately every 90 minutes. Researchers propose that each phase of a sleep cycle may contribute to memory formation and encoding in a unique way, although these contributions have yet to be clearly identified (Walker, 2005).

The fact that memories are encoded and transformed after acquisition is clearly demonstrated by neural imaging studies that demonstrate that brain activation during skill acquisition is different from patterns of brain activation during skill recall (Fischer et al., 2005; Karni et al., 1995; Karni et al., 1998; Muellbacher et al., 2002; Pascual-Leone, Dang, Cohen, Brasil-Neto, & et al., 1995; Penhune & Doyon, 2002; Shadmehr & Holcomb, 1997; Walker & Stickgold, 2006). Cortico-cerebellar networks are actively engaged when learners first practice a new motor skill. During recall of that skill, cortico-cerebellar activation is replaced with cortico-striatal activation. The interactions between cortico-cerebellar and cortico-striatal networks begin in the hours subsequent to practice. Bursts of task-related neural activity persist during this time as motor memories begin to shift to other areas of the brain (Peigneux et al., 2006). When a task is recalled, brain areas known to represent conscious regulation and self-monitoring of movements are not active to the extent they were during acquisition (Fischer et al., 2005). Quite literally, memories for new skills shift to different areas of the brain during time awake and during sleep.

Studies of motor skill learning that examine variables associated with sleep-based memory consolidation offer interesting insight into this phenomenon. It is important to note that in studies of memory consolidation, learners typically engage in self-regulated practice of quite simple motor skills (i.e., participants select and adjust performance parameters at will). Results described in the following paragraphs were obtained using research paradigms quite different from those used in the motor learning literature described previously, where learners engaged in systematically controlled practice.

Learning is impaired if sleep is deprived the night before acquisition of new motor skills (Walker & Stickgold, 2006). When learners do not sleep before they practice a new skill for the first time, memory encoding during acquisition is impaired. If sleep is deprived the night immediately following acquisition, learners do not demonstrate performance enhancements (Maquet, Laureys et al., 2003). When sleep is deprived the first night following acquisition and recovery sleep occurs the second night, learners who were deprived on the first night do not demonstrate the same extent of performance enhancement as learners who slept the first night post-training (Fischer et al., 2005). Patterns of neural activation between sleep-deprived and non-deprived participants differ (Maquet, Peigneux et al., 2003).

Motor skill performance is enhanced most when sleep occurs during the night immediately subsequent to acquisition. Consolidation that occurs during additional nights of sleep beyond that first night continue to enhance performance, but to a lesser degree (Duke & Davis, 2006; Walker, Brakefield, Seidman et al., 2003).

Consolidation-based enhancements are specific to practiced tasks and do not transfer to similar tasks performed with the same hand or to identical tasks performed with the contralateral hand (Fischer et al., 2002; Karni et al., 1998). This lack of transfer illustrates that neural representations for individual motor skills are uniquely stored in the brain (Karni et al., 1995).

Increasing the amount of practice during acquisition does not yield differences in the extent that sleep-based consolidation enhances performance when skills are recalled (Savion-Lemieux & Penhune, 2005; Walker, Brakefield, Seidman et al., 2003), and the extent to which consolidation enhances motor skills is not related to the extent to which skills improve during acquisition (Walker, Brakefield, Seidman et al., 2003). Sleep-dependent memory consolidation enhances performance of more complex finger skills to an even greater degree than it does less complex finger skills (Kuriyama et al., 2004).

In addition to observing sleep-based consolidation enhancements in motor skill performance, Hotermans et al. (2006) observed that participants who recalled a finger sequence after a brief rest period (5 and 30 minutes) demonstrated enhancements in performance. That boost in performance was temporary, though, disappearing after four hours of wakefulness. The authors also observed that the temporary performance boost observed after brief rest intervals was similar in extent to the performance enhancements observed when the skill was recalled following sleep-based consolidation. Similarly, Davis (2007) observed enhancements in performance following 5-minute rest periods that were inserted into an initial practice session, regardless of whether the rest period was inserted early in initial the practice session or later in those sessions. The biological mechanisms that may serve to elicit boosts in performance have yet to be identified.

Neural Changes During the Slow Learning Phase

Sleep-dependent memory consolidation has been demonstrated in humans, non-human primates, cats, rats, mice, and zebra finch (Walker & Stickgold, 2006). Non-human studies of memory consolidation and development offer more detailed information about the neural processes that underlie memory formation, as this research is typically more invasive than that conducted with human participants. These studies more completely describe neural processes that occur during the *slow learning* phase of motor skill development. Slow learning begins following acquisition, and continues as learners engage in practice of a skill over an extended period of time. This phase of motor learning is characterized by incremental performance gains that occur across many practice sessions. Neural activity that underlies these changes is characteristically different than activity observed during skill acquisition.

Studies of complex motor learning with rats demonstrate that extensive motor skill training over many days induces synaptogenesis and motor map reorganization within the motor cortex (Kleim et al., 2004); synaptogenesis and motor map reorganization are not present during the fast learning stage when skills are acquired.

Protein synthesis begins during acquisition and continues for hours and days afterward. Protein synthesis initiates the formation of new synapses between existing neurons. Neural representations for skills become more extensive as more synapses form between neurons. Synaptogenesis and motor map reorganization are distinct neural processes unique to the slow learning phase. It is interesting to note that rapid gains in performance do not occur simultaneously with extensive changes in neural activity; rather, those large gains in performance during the fast learning stage initiate neural processes that change the functional and structural organization of the brain over time.

Imaging studies with humans also illustrate that neural representations for motor skills continue to change over the course of slow learning (Floyer-Lea & Matthews, 2005; Karni et al., 1995; Karni et al., 1998). Karni et al. (1995) provided evidence of a gradual evolution of the representation of a learned finger sequence that occurred with extended practice over the course of many weeks. The result of slow learning was an expanded neural representation for the sequence in primary motor cortex. The area of neural activation elicited by performance was enlarged compared to initial activation, with a more extensive network of neurons in M1 recruited to represent the learned task. Activation patterns that occur during fast learning are movement-specific, whereas activation patterns that occur during slow learning indicate increased bihemispheric activity in both motor and somatosensory networks (Floyer-Lea & Matthews, 2005). These differences in activation support the idea that neural networks are plastic and are modified through experience.

Memory Consolidation Research Summary

It is now widely accepted that neural networks in the brain are modified through experience. Put simply, forming memories for new skills requires structural and functional reorganization in the brain.

Performance of a new skill improves rapidly in the initial stages of practice. Those performance improvements are the result of changes in brain activation elicited by repeated execution of the skill. The rate of performance improvement begins to level off during initial practice as a distinct neural representation for the practiced skill is formed. Memory consolidation is triggered during practice and continues after practice has ended; this process modifies the neural representation, or memory, for the new skill in ways that affect performance when skills are recalled.

Memory consolidation occurs in two stages. The first stage, consolidation-based stabilization, makes new memories resistant to interference and sustains levels of performance achieved by the end of initial practice. Consolidation that occurs during this phase happens during waking hours and continues for 4-6 hours after the end of practice. The second phase, consolidation-based enhancement, modifies memories in ways that enhance performance when skills are recalled. This phase of consolidation most often relies on neural processes that occur during sleep.

Relevance of Memory Consolidation Research To This Study

The research on procedural memory to date has examined consolidation effects with relatively simple motor skills (i.e., skills that comprise limited movement parameters and degrees of freedom) learned by participants who had had little previous practice with the experimental tasks prior to training. It is unknown whether the observable effects of sleep-based consolidation are limited to inexperienced learners or whether these effects are robust and observable in more experienced participants performing more complex and familiar skills.

Studies that examine memory consolidation effects have yet to manipulate practice in a systematic way, as have researchers who study human movement and motor control. Participants in studies of memory consolidation typically perform skills as quickly and accurately as possible. Learning skills at rates that are regulated externally (i.e., under stable and variable practice schedules) may affect memory consolidation processes in ways that have not yet been observed. Does the time course of memory consolidation change when learners acquire new skills under practice schedules that require different levels of motor control?

SUMMARY

Motor skill performance in music depends heavily on practice, yet there is a paucity of empirical research in music that addresses how the content of practice directly affects a musicians' ability to recall performance skills. Research that examines the practice of professional and near-professional musicians has shown that professional musicians use effective practice strategies that facilitate the achievement of short term goals within each practice session and long term goals related to performing beautifully and fluidly on stage. The decisions they make about technique occur early in the learning process and are repeated consistently as practice continues so that the motor skills they use to execute passages of music are well remembered. Professional and near-professional musicians engage metacognitive skills to monitor and adjust practice strategies as needed to achieve their long term goals.

Extant research in music does not yet explain how the content of practice affects memory and skill development in music performance. Some practice strategies that have been identified as effective means of facilitating memory and skill development in other disciplines (e.g., distributing practice over time, systematically varying the way a skill is executed during practice) have not been explored thoroughly by music researchers.

Researchers who study human movement and motor control have shown that the development of motor memory and performance skills depends on complex interactions between the sophistication of learners, the complexity of the skills they acquire, and the cognitive requirements that different practice schedules impose. As learners become increasingly sophisticated, they are able to acquire increasingly complex skills and negotiate the higher cognitive demands required by variable practice. It remains to be seen how task-related knowledge and experience with specific motor skills mediate the complex relationships that exist between learner sophistication, task complexity, and practice variability.

Memory consolidation research indicates that memory and skill development continue to change after physical practice has ended. Consolidation that occurs during time awake renders memories resistant to interference and maintains performance levels achieved during acquisition, and consolidation that occurs during sleep may enhance performance beyond that achieved during acquisition. Memory formation and consolidation have been studied using motor skills more simple in nature than music performance skills; those studies have demonstrated consolidation effects only with learners who had no previous experience with the experimental task. Simmons and Duke (2006) were the first to observe consolidation effects with experienced learners.

The study reported here was designed to draw upon the principles of human learning demonstrated in other disciplines and to apply them in the context of music learning. Testing the effects of memory consolidation and practice variability in the context of music performance offers new information about cognitive processes that underlie complex motor task performance and contributes to our understanding of human learning.

Chapter III: Method

Findings in neuroscience suggest that wake-based consolidation, a process of memory formation that begins during active practice and continues during waking hours subsequent to the cessation of practice, renders procedural memories resistant to interference and forgetting. Skills levels obtained by the end of active practice are typically maintained following wake-based consolidation. Sleep-based consolidation, which may occur during daytime naps or overnight sleep, has been shown to enhance procedural memories, resulting in improved performance following sleep, even absent further practice (Fischer, Hallschmid, Elsner, & Born, 2002; Walker, Brakefield, Hobson, & Stickgold, 2003; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002; Walker, Brakefield, Seidman et al., 2003). These effects have been demonstrated repeatedly in the performance of simple motor tasks, in which participants perform brief manual sequences "as quickly and accurately as possible." In these experiments, participants selected and adjusted their performance speed at will, with their judgments presumably based on balancing speed and accuracy.

In attempting to characterize the nature of the cognitive organization of motor skill memory, researchers in kinesiology have adopted a somewhat different approach to the study of motor learning. Participants typically practice prescribed performance tasks under highly structured conditions that include systematically varied performance parameters. The findings of this research, done primarily with simple motor tasks, demonstrate quite consistently that learners who engage in variable practice demonstrate better performance when tasks are recalled than do learners who engage in stable practice.

The effects of practice variability on performance have been investigated in numerous physical, perceptual, and cognitive skills, ranging from highly contrived movements (e.g., pursuit rotor tasks) to more common behaviors (e.g., batting in baseball). Participants in these studies engaged in structured practice of assigned motor tasks during which investigators systematically varied performance parameters. It is important to note that in much of this research, retests occurred 24 hours after acquisition. In other words, the time between acquisition and recall included sleep-based memory consolidation.

Studies in neuroscience that examine the effects of memory consolidation on learning have yet to manipulate practice in a systematic way. In all studies conducted to date, learners' practice speeds were self-regulated. Studies in motor learning that examine the effects of practice variability on learning have yet to examine how memories for newly acquired skills are changed during the waking hours immediately subsequent to practice. Whether the time course of memory consolidation is modified for skills learned under systematically controlled conditions remains unknown.

Motor skill performance in music depends heavily on the ability to retain improvements achieved during active practice in subsequent practice sessions and, ultimately, in performance. Examining the effects of distributing practice across hours and days (to allow time for wake- and sleep-based memory consolidation) and systematically varying the way motor skills are executed during practice offers new information about cognitive processes that underlie procedural learning. There is as yet no clear understanding of the relationship between practice variability and the processes of memory consolidation.

Participants

Participants (*N* = 92) were music majors at The University of Texas at Austin (*n* = 50 males). All were right-handed, between 18 and 40 years of age, and had no neurological, psychiatric, or sleep-disorder histories. All reported no extensive training or experience on the piano beyond a maximum of five semesters of undergraduate group piano instruction.

Three experiments were designed to examine the effects of memory consolidation and practice variability on the retention of a motor sequence. I created nine experimental conditions by pairing each of three practice schedules (self-regulated, stable, and variable practice) with each of three inter-session interval conditions (5 minutes, 6 hours, and 24 hours; see Table 1). Conditions were assigned randomly to 92 participants, with approximately 10 participants in each condition; exceptions were made to accommodate participants' schedules in approximately 10 cases.

All participants learned a 9-note sequence on a digital piano, which they practiced in three, 15-20 minute sessions. Each practice session consisted of three blocks of 15 performance trials. Each block was separated by 30 seconds of rest. Each performance trial was followed by 3 seconds of silence and the subsequent presentation of an auditory and visual cue for the next performance trial to begin. At the conclusion of each session, participants completed a post-test that consisted of five additional performance trials in which participants were instructed to perform “as quickly, accurately, and evenly as possible.” The three sessions were separated by three different time intervals to assess possible effects of sleep- and wake-based memory consolidation. For approximately one third of the participants, the three sessions were separated by 5 minutes of rest (massed practice); for another third, sessions were separated by 6 hours (wake-based consolidation); and for the remaining participants, sessions were separated by 24 hours (wake- and sleep-based consolidation).

Participants learned under one of three practice conditions. Approximately one third of the participants practiced the sequence at self-regulated speeds, with the goal of playing “as quickly, accurately, and evenly as possible”; another third practiced at each of three tempo designations (M.M. = 52, 72, and 92; equivalent to 208, 288, and 368 key presses per minute and 2308, 1667, and 1304 ms, respectively) with one tempo practiced in each 15-trial block (stable practice); the remaining third practiced at the same three tempos, but the tempo varied from trial to trial within each block in a quasi-random arrangement (variable practice). Following each session, all participants performed 5 trials “as quickly, accurately, and evenly as possible.”

Table 1: Practice and Inter-Session Interval Condition Assignments.

Practice Condition	Session	Inter-Session Interval	Session	Inter-Session Interval	Session
Experiment 1 Self-regulated Practice	1	5 minutes	2	5 minutes	3
		6 hours		6 hours	
		24 hours		24 hours	
Experiment 2 Stable Practice	1	5 minutes	2	5 minutes	3
		6 hours		6 hours	
		24 hours		24 hours	
Experiment 3 Variable Practice	1	5 minutes	2	5 minutes	3
		6 hours		6 hours	
		24 hours		24 hours	

Note: 24-hr intervals include overnight sleep.

So as not to introduce tempo variations before performance of the task stabilized, all participants in the stable and variable practice experiments performed all 15 trials in the first block of Session One at M. M. = 52. This facilitated acquisition of this complex motor skill prior to introducing changes in speed (Lai, Shea, Wulf, & Wright, 2000). Following the first block of practice in the training session, participants in the stable practice experiment negotiated changing tempo parameters with each new practice block, and participants in the variable practice experiment negotiated changing tempo parameters with each performance trial for the remaining blocks of practice in the three sessions (see Appendix A).

Participation in this study was voluntary. Prior to the first session, I asked all participants to abstain from engaging in behaviors that are known to diminish cognitive function and motor performance. Participants agreed to avoid drinking alcoholic and caffeinated beverages and to avoid using other mind-altering drugs for 12 hours prior to and for the duration of their participation in the study. Participants whose practice sessions were separated by 6 hours agreed to avoid napping between sessions, and participants whose sessions were separated by 24 hours agreed to sleep at night between sessions.

Participants were able to complete the three practice sessions in one hour or less. Upon completion of the study, participants received $12 compensation. Prior to the beginning of the first session, all participants signed a consent form that noted approval by The University of Texas at Austin Institutional Review Board.

SETTING

I made individual appointments with every participant. Participants either met with me or with one of two other graduate students who served as test proctors. All meetings were conducted in a small, quiet, windowless room in the music building at The University of Texas at Austin. The room was chosen to prevent extraneous sounds and movement from distracting participants.

I used the Midiman USB Midisport 2x2 MIDI Interface to connect a Macintosh 12" PowerBook G4 computer (model number A1010) to a Roland KR-4700 Digital Piano for data collection. Participants completed all practice sessions on the Roland piano. The sequence, target tempos, and feedback were presented to participants on the laptop computer using Max/MSP software; the computer was located on top of the keyboard where sheet music is typically positioned. The software also recorded MIDI performance data from each session.

The sound of a metronome and the sound of participants' performance were heard through the computer. Participants listened to all electronic cues (sound of the metronome, the sound of the piano during every performance trial, and a bell-like tone that sounded during the post-test) through Bose QuietComfort Headphones (model number QC-2). The test proctor listened through a second set of headphones.

PROCEDURES FOR DATA COLLECTION

Participants signed an official consent form approved by The University of Texas at Austin Institutional Review Board at our first meeting (see Appendix B). Before they began each practice session, they rated their feeling of alertness using the Stanford Sleepiness Scale (Hoddes, Dement, & Zarcone, 1972) and answered questions about their music backgrounds. The test proctor also recorded the following information: name, gender, handedness, reports of compliance with study criteria (e.g., no consumption of caffeine, alcohol, drugs), and reports of sleep time for the previous night (see Appendix C).

Participants' task was to learn a 9-note sequence on the digital piano with their left (non-dominant) hand (see Figure 1) and to practice this same sequence for the duration of the three practice sessions. Each practice session consisted of three blocks of 15 performance trials; each block was separated by 30 seconds of rest; and each performance trial was separated by 3 seconds of silence. Following each session, all participants were instructed to perform 5 trials "as quickly, accurately, and evenly as possible."

Before the first session began, the test proctor oriented participants to the visual presentation on the computer screen and read the following instructions:

> You will learn a short sequence of notes on this keyboard. You will play the sequence with your left hand and will use the fingerings written under the staff.

Participants then played through the sequence one time as slowly as needed to play the correct notes with the correct fingerings. If the participant struggled to do this initially, feedback was offered and repetitions were allowed until one correct execution of the sequence was achieved. During this time, participants were free to ask questions about the procedure and the sequence. The remaining instructions to the self-regulated practice learners (Experiment 1) were as follows:

> The sequence and fingering indications will be displayed continuously on the computer screen. Your goal is to play the sequence as quickly, accurately, and evenly as possible. You will hear a ding and see the word "ready" appear on the computer screen above the sequence. This indicates that the computer is ready to record your performance. You may then start playing when you are ready. When you finish playing the sequence, please wait for the word "ready" to appear and for the auditory cue to sound before beginning your next trial.
>
> The dots that you see above the staff correspond to each note. They will light up from left to right with each note you play on the keyboard. The lights will be illuminated regardless of whether you play the correct pitch; they are only there to help you keep track of where you are in the sequence. The computer will only record the first 9 notes that you play, so it is important that you not start over again or try to replay a note that you might miss. Do your best to play the melody from beginning to end each time without stopping. Do not practice specific parts out of context or vary the rhythm pattern; in other words, play it just as written.

The remaining instructions to stable practice learners (Experiment 2) and variable practice learners (Experiment 3) were as follows:

> The sequence and fingering indications will be displayed continuously on the computer screen. The computer will also display a target tempo for each performance trial. Your goal is to play the sequence at the target tempo as accurately and evenly as possible. A metronome will sound quarter notes at the target tempo, indicating that the computer is ready to record your performance. After the metronome begins, you may start playing when you are ready. When you play the first note of the sequence, the metronome will stop sounding. When you have completed each trial, the computer will display the actual tempo of your

> performance in the box immediately below the target tempo. Your goal is to match your performance tempo with the target tempo, and play as accurately and evenly as you can. This feedback will be displayed for a few seconds, and will disappear when the target tempo for the next performance trial is presented and the metronome begins to sound. Listen to the metronome long enough to orient yourself to the tempo and begin to play when you are ready.
>
> The dots that you see above the staff correspond to each note. They will light up from left to right with each note you play on the keyboard. The lights are there to help you keep track of where you are in the sequence. The lights above each note will be illuminated regardless of whether you play the correct pitch. The computer will only record the first 9 notes that you play, so do your best to play the melody from beginning to end each time without stopping; do not practice specific parts out of context. Do not vary the rhythm pattern; in other words, play it just as written.

Before data collection began, participants performed two test trials with the computer program so they could orient themselves to the way the program worked. Participants in the stable and variable practice experiments were told that they would practice the sequence at three different tempos. Stable practice learners were told that the tempo would change after each set of 15 trials. Variable practice learners were told that after the first practice block of training the tempo would change for each trial in random order.

At the end of Sessions 1 and 2, participants in the 5-minute rest interval groups were given a break, during which practice was prohibited. Participants either sat and made general conversation with me, got up to stretch their legs, or excused themselves for a restroom break. Participants in the 6-hour rest interval groups were reminded to avoid napping, to abstain from drinking caffeinated or alcoholic beverages and from using other mind-altering substances, and to refrain from practicing the sequence between sessions. Participants in the 24-hour rest interval groups were reminded to abstain from drinking caffeinated or alcoholic beverages and from using other mind-altering substances, to refrain from practicing the sequence between sessions, and to note how long they slept that night.

Figure 1: The 9-note sequence participants practiced in all three experiments. The numbers below the staff indicate the finger used to play each note.

In Experiment 1 (self-regulated practice), Sessions 2 and 3 were conducted in the same manner as Session 1. In Experiments 2 (stable practice) and 3 (variable practice), there was a slight difference in the way sessions were conducted. The first block of practice (15 trials) in Session 1 occurred at M.M. = 52 for both stable and variable practice participants. In blocks 2 and 3 of Session 1, participants in the stable practice condition performed the sequence at M.M. = 72 and 92, and participants in the variable practice condition negotiated the quasi-random presentation of trials at all three tempos. In Sessions 2 and 3, stable and variable practice participants performed an equal number of trials at each pre-designated tempo that were presented according to practice conditions previously described (see Appendix A).

COMPUTER PROGRAM

A computer programmer at The University of Texas at Austin wrote a program specifically for the purposes of this investigation using Max/MSP software. The program was set up to display the sequence (all groups) and target tempos (for stable and variable practice conditions), to run the protocol for each experimental condition, to provide feedback to participants (performance speed for self-regulated conditions and tempo accuracy for stable and variable conditions), and to collect MIDI performance data.

The computer continuously displayed the sequence in music notation for all nine groups. Also displayed were dots that appeared above each note on the staff. The dots illuminated in red from left to right with each keypress to help participants keep track of where they were in the sequence as they practiced. The lights above each note were illuminated regardless of whether the correct pitch was played. The computer stopped recording on each trial after the first nine notes were played.

For self-regulated practice learners (Experiment 1), each performance trial was initiated by the appearance of the word "Ready" above the staff and the sound of a bell-like tone. Each trial was followed by three seconds of silence, then the word "Ready" appeared and the tone sounded to prompt participants for the next trial.

For stable and variable practice learners (Experiments 2 and 3), the computer display also included a numeric indication of the target tempo designated for each performance trial. The sound of a metronome at the target tempo initiated each performance. Three seconds of silence followed each trial. During that time, the computer displayed feedback about the actual tempo of participants' performance (in terms of a metronome marking) underneath the numeric display of the target tempo. After three seconds, the target tempo for the next trial was displayed and the metronome clicks began at the target tempo.

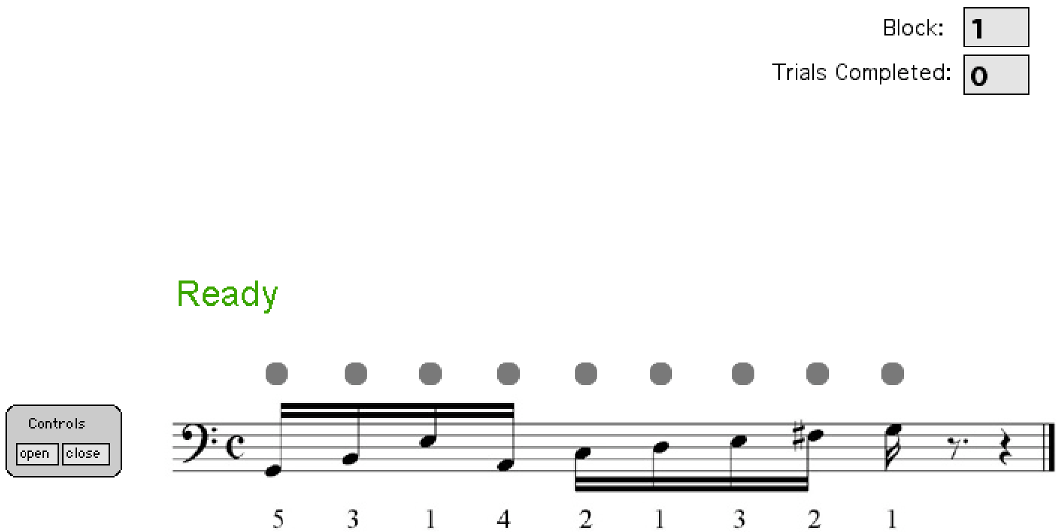

Figure 2: Computer screen viewed by self-regulated participants.

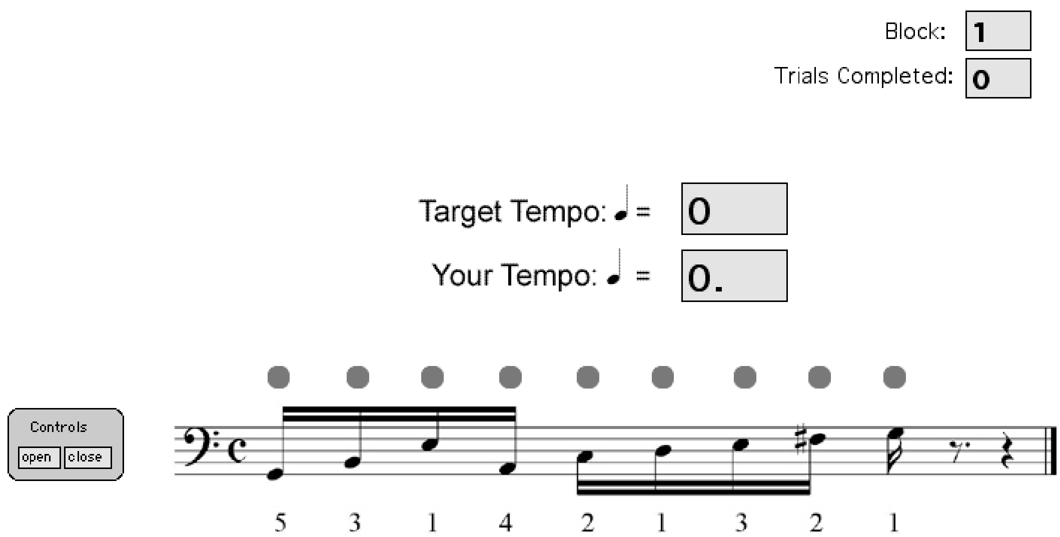

Figure 3: Computer screen viewed by stable and variable practice participants.

The software recorded MIDI (Musical Instrument Digital Interface) data during all three sessions. Data for the following variables were analyzed in Experiment 1 (self-regulated practice): accuracy, defined as the number of keypress errors per sequence, and speed, defined as the time elapsed between first and last key presses in each sequence (expressed in milliseconds). Data for the following variables were analyzed in Experiments 2 and 3 (stable and variable practice): accuracy, defined as the number of keypress errors per sequence, and tempo accuracy, defined as the difference between the predetermined target duration of each sequence and the actual duration of each sequence (expressed in milliseconds). The software recorded data for individual trials and calculated block and session means for each variable.

The software had two reset features. If participants got a false start on a trial, the proctor was able to reset that trial and have the participant start again. The criterion for a false start was that participants stopped playing altogether after playing no more than two notes, regardless of note accuracy. Trials were typically reset for false starts one or two times in any given session for about half of the participants. In only a few cases were several trials reset for false starts; even in these situations, though, the number of resets did not exceed 10 across all three sessions (135 total trials).

In cases where a given trial was markedly different from all other trials, the proctor was able to remove the data for that trial from calculations of block and session means. The criteria for this reset function were fairly subjective. After the first block of Session 1, most participants established levels of note accuracy, tempo accuracy, and performance speed that did not vary greatly from trial to trial. In other words, participants' trial-to-trial performances were relatively consistent, with gradual improvements in performance occurring over time. In rare instances, a participant would perform a trial that was clearly aberrant, perhaps due to lack of concentration, readiness, or fatigue. This reset function was used one or two times for very few participants across all three sessions. The proctors' handwritten notes were used to generate the preceding information on reset function use.

In situations where two keys were pressed within 50 milliseconds of each other (i.e., when a participant played two notes at virtually the same time; "finger misfires"), only the second of the two notes was recorded. If the second note was indeed the next note in the sequence, no error was recorded. If it was not, one error was recorded. For most participants, finger misfires occurred quite infrequently, if ever. Finger misfires were a common occurrence for only two participants.

The method used in this investigation was inspired by and modeled after several studies of procedural learning that describe significant enhancements in performance that were observed when newly acquired skills were recalled, absent additional practice following skill acquisition (Duke & Davis, 2006; Shea, Lai, Black, & Park, 2000; Simmons & Duke, 2006; Walker, Brakefield, Hobson et al., 2003). The premise of this study was to draw together the principles of human learning these studies describe to better inform our understanding of how memories for newly acquired skills change over time and how performance is most efficiently improved over time and across practice.

Chapter IV: Results

The refinement of skill performance in music requires that learners improve performance during practice and retain improvements over time. This study was designed to test distribution of practice and practice variability, principles of human learning that have been scarcely addressed in music research, though they have been studied more thoroughly in other domains. Testing these effects in music performance offers new information about cognitive processes that underlie procedural learning in the context of complex motor task performance.

Three experiments were conducted to address the following research questions:

1. Experiment 1: To what extent are complex motor skills affected by wake- and sleep-based consolidation processes in learners with extensive task-related knowledge and moderate levels of task-related skill?
2. Experiment 2: To what extent are consolidation-based enhancements affected by stable practice procedures, in which the speeds of learners' practice trials are externally regulated and practiced in a sequence that includes minimal variation in the way skills are executed from trial to trial?
3. Experiment 3: To what extent are consolidation-based enhancements affected by variable practice procedures, in which the speed of learners' practice trials are externally regulated and practiced in a sequence that includes maximum variation in the way skills are executed from trial to trial?

Experiment 1: Self-Regulated Practice and Memory Consolidation

The results I obtained in this experiment are consistent with the findings of many studies in which novice learners practiced more limited tasks unrelated to music performance, and to the findings reported in Simmons and Duke (2006), in which musicians practiced a keyboard melody. In short, I observed that memory consolidation enhanced note accuracy in the performances of participants who slept between Sessions 1 and 2. All three groups demonstrated enhanced performance speed in Session 2, and the 6-hour and 24-hour groups continued to demonstrate speed enhancements in Session 3. A more complete description of my results follows.

Self-reports of Sleep and Alertness

There were no differences between groups in the amount of sleep participants reported for the night before Session 1, $F(2, 24) = .479$, $p > .625$. There were no significant correlations between reported sleep and note accuracy: Session 1, $r = -.186$, $p > .352$; Session 2, $r = -.582$, $p > .078$; Session 3, $r = .119$, $p > .743$. There were also no significant correlations between reports of sleep and speed: Session 1, $r = -.372$, $p > .056$; Session 2, $r = -.217$, $p > .548$; Session 3, $r = -.291$, $p > .414$.

I compared participants' reports of alertness on the Stanford Sleepiness Scale given at the beginning of each session with corresponding note accuracy and speed data. There were no significant correlations between reports of alertness and note accuracy data: Session 1, $r = -.104$, $p > .590$; Session 2, $r = -.195$, $p > .411$; Session 3, $r = .064$, $p > .790$. Similar results were observed between reports of alertness and speed data: Session 1, $r = -.266$, $p > .163$; Session 2, $r = -.337$, $p > .146$; Session 3, $r = -.274$, $p > .242$. These results suggest that the extent to which participants felt alert had no consistent effect on their performance.

Excluded Data

A descriptive analysis by group identified two participants as outliers in at least one group session mean. These two participants (one from the 5-minute group and one from the 6-hour group) were also outliers in terms of block means; their performance in at least 2 blocks was in excess of two standard deviations away from group block means. Based on these criteria their data were excluded, leaving 29 participants in the analysis for the self-regulated learners (5-minute group, $n = 9$; 6-hour group, $n = 10$; 24-hour group, $n = 10$).

There were problems with the five post-session trials for all of the participants that preclude a meaningful analysis. The data from these trials will not be discussed further.

Note Accuracy

Means for 5-minute, 6-hour, and 24-hour groups are presented in Figure 4. I compared the note accuracy in participants' performances within each intersession-interval condition using one-way, repeated measures ANOVAs and post hoc one-tailed *t*-tests with appropriate Bonferroni corrections.

There were no significant differences among the three note accuracy session means for the 5-minute group, $F(2, 16) = 0.96$, $p > .405$. It should be noted that the error rate in this group in the first practice session was near zero, much lower than that of the other two groups.

Likewise, there were no significant differences among the three note accuracy session means for the 6-hour group, $F(2, 18) = 0.29$, $p > .754$. As was the case in the 5-minute group, there were no discernible improvements in note accuracy from one session to the next.

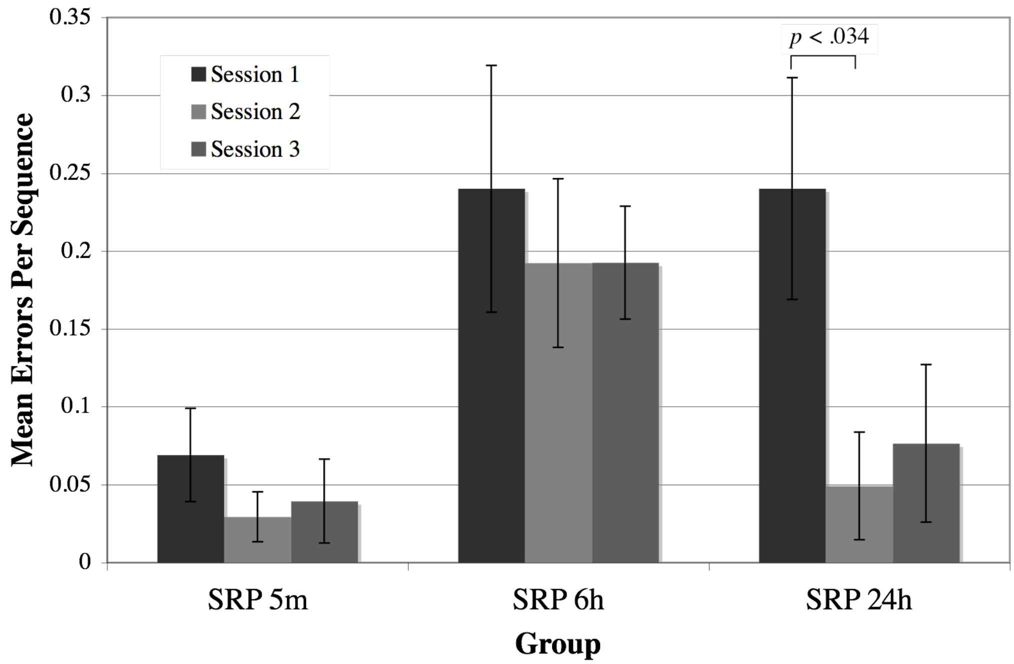

Figure 4: Note accuracy session means for the self-regulated practice experiment. Error bars represent ±1 standard error of the mean.

I found a significant difference among the three note accuracy session means for the 24-hour group, $F(2, 18) = 4.92$, $p < .021$. Post hoc analyses indicate that the mean for the first practice session was significantly higher than the mean for Session 2, $p < .034$, and Session 3, $p < .046$, which were not significantly different from one another, $p > .500$.

In this analysis, it is important to note that all trials from Session 1 were included in the comparison. Memory consolidation research in neuroscience, and similar studies in music (e.g., Duke & Davis, 2006; Simmons & Duke, 2006), compared only the last three blocks (out of 12 total practice blocks) of Session 1 with brief, 3-block retests in two subsequent sessions. In this study, as in Shea, Lai, Black and Park (2000), the very first trials in the learning process were included in the analysis.

As the data in Figure 4 clearly show, participants in the three groups did not perform similarly in Session 1, most likely due to a selection variable that I will address later in the document; therefore, direct comparisons of note accuracy between the 5-minute group and the other two groups are not possible. Mean note accuracy data for the 6-hour and 24-hour groups, whose Session 1 performances were similar, demonstrate clear differences in the effects of wake- and sleep-based consolidation; put simply, memory consolidation enhanced Session 2 performance for participants who slept between sessions. This result is consistent with data reported in Simmons and Duke (2006) and a larger body of research performed with simple motor skills.

Note accuracy session means reveal that the 24-hour group, whose participants slept between Sessions 1 and 2, made the largest improvements in performance between sessions. Smaller, nonsignificant gains were observed in the 6-hour group, who remained awake between sessions. These results suggest that sleep-based consolidation enhanced Session 2 performance in the 24-hour group, whereas wake-based consolidation did not lead to performance enhancements in the 6-hour group.

Smaller changes in performance were observed between Sessions 2 and 3 for all three groups. It seems that a second night of sleep-based consolidation did not lead to continued performance enhancements between Sessions 2 and 3 in the 24-hour group, nor did wake-based consolidation lead to Session 3 enhancements in the 6-hour group.

Speed

Means for 5-minute, 6-hour, and 24-hour groups are presented in Figure 5. I compared participants' performances in terms of speed within each intersession-interval condition using one-way, repeated measures ANOVAs and post hoc one-tailed *t*-tests with appropriate Bonferroni corrections.

There was a significant difference among the three speed session means in the 5-minute group, $F(1, 8)$[1] $= 27.68$, $p < .002$. Post hoc analyses indicate that the mean for Session 1 was significantly higher (indicating slower performance) than the means for Session 2, $p < .002$, and Session 3, $p < .001$, which were not significantly different from one another, $p > .231$.

There were also significant differences among the three speed session means in the 6-hour group, $F(1, 9)$[1] $= 28.32$, $p < .001$. Post hoc analyses indicate that the means for Sessions 1, 2, and 3 were all significantly different from one another: Session 1 vs. Session 2, $p < .001$; Session 1 vs. Session 3, $p < .001$; and Session 2 vs. Session 3, $p < .003$.

There were significant differences among the three speed session means in the 24-hour group, $F(1, 9)$[1] $= 18.39$, $p < .003$. Post hoc analyses indicate that the means for Sessions 1, 2, and 3 were all significantly different from one another: Session 1 vs. Session 2, $p < .004$; Session 1 vs. Session 3, $p < .003$; and Session 2 vs. Session 3, $p < .004$.

[1] Corrected *df* for violation of the sphericity assumption (Lower-bound).

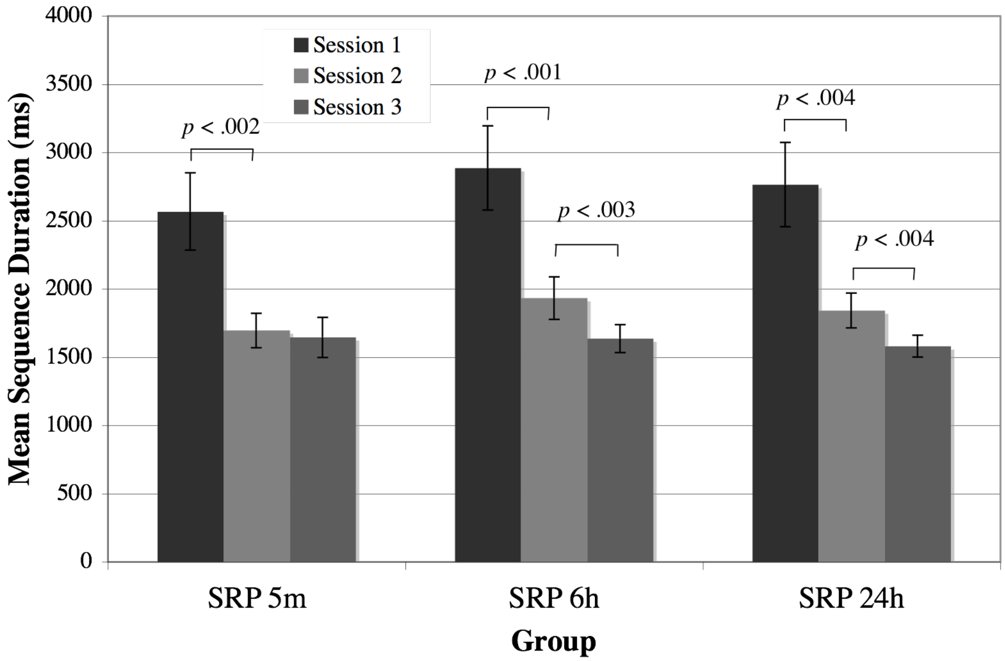

Figure 5: Speed session means for the self-regulated practice experiment. Error bars represent ±1 standard error of the mean.

Session means for speed reveal that the extent of performance speed change between Sessions 1 and 2 was similar in all three groups, whereas the 6-hour and 24-hour groups showed larger gains in speed between Sessions 2 and 3 than did the 5-minute group. The observation of speed enhancements in the 6- and 24-hour groups are consistent with another study performed using simpler motor skills, which demonstrates sleep enhancements following wake-based memory consolidation (Fischer, Hallschmid, Elsner, & Born, 2002). Perhaps both wake- and sleep-based memory consolidation facilitated the larger gains in speed observed between Sessions 2 and 3 in the 6- and 24-hour groups.

I observed significant, positive correlations between note accuracy (number of errors per sequence) and speed (sequence duration, ms) in Sessions 1 and 2: Session 1, $r = .421$, $p < .024$; Session 2, $r = .432$, $p < .020$. In these sessions, participants who made fewer errors also tended to perform faster (less time in ms) than did participants who made more note errors. That relationship was not evident in Session 3, $r = -.119$, $p > .539$, which is perhaps attributable to the lack of change in note accuracy performance in all groups between Sessions 2 and 3.

EXPERIMENT 2: STABLE PRACTICE AND MEMORY CONSOLIDATION

The enhancing effects of memory consolidation on motor skill performance have been repeatedly observed when learners engage in self-regulated practice. What remains unknown is whether this effect is present when learners engage in other kinds of practice, namely, practice that is externally regulated and systematically varied. Experiment 2 was designed to examine the effects of memory consolidation on procedural skills learned under controlled practice conditions in which learners performed multiple trials at a given tempo before practicing at different tempos.

In short, I observed performance enhancements in note accuracy and tempo accuracy for all three inter-session intervals, regardless of whether the intervals between sessions included time for wake- and sleep-based memory consolidation. This pattern of skill improvement is quite different from patterns observed when learners engage in self-regulated practice, which suggests that beneficial effects of memory consolidation may be mediated by practice that occurs under systematically controlled conditions, or that memory consolidation processes operate under a different time course with stable practice. A more complete description of these results follows.

Self-reports of Sleep and Alertness

There were no differences between groups in the amount of sleep participants reported for the night before Session 1, $F(2, 25) = 1.05$, $p > .365$. Reported sleep was unrelated to note accuracy performance: Session 1, $r = .119$, $p > .545$; Session 2, $r = -.465$, $p > .293$; Session 3, $r = -.010$, $p > .983$. There were also no significant correlations between reported sleep and tempo accuracy: Session 1, $r = -.097$, $p > .624$; Session 2, $r = -.628$, $p > .131$; Session 3, $r = -.410$, $p > .360$.

I compared participants' ratings of alertness in each session with corresponding note accuracy data and found no relationship between these variables: Session 1, $r = -.083$, $p > .673$; Session 2, $r = .194$, $p > .440$; Session 3, $r = -.137$, $p > .587$. There was also no significant relationship between alertness and tempo accuracy data in Sessions 1 and 2: Session 1, $r = .087$, $p > .659$; Session 2, $r = -.255$, $p > .308$. In Session 3, I found a significant moderate correlation between alertness and tempo accuracy: Session 3, $r = .529$, $p < .025$. Although this may be a spurious result, this finding indicates that participants who reported greater alertness (represented by lower numbers on the alertness scale) tended to perform with more tempo accuracy (represented by a smaller difference between the goal tempo and the actual tempo) than did participants who reported lower levels of alertness. The fact that there were no consistent relationships between alertness reports and note or tempo accuracy data makes the one significant correlation difficult to explain.

Excluded Data

Three participants were identified as outliers for at least one group session mean; all three participants were from the 24-hour group. As in Experiment 1, their performance in at least 2 blocks was in excess of two standard deviations away from group block means. Based on these criteria their data were excluded from this analysis, leaving 28 participants in the stable practice condition (5-minute group, $n = 10$; 6-hour group, $n = 11$; 24-hour group, $n = 7$).

There were problems with the five post-session trials for all of the participants that preclude a meaningful analysis. The data from these trials will not be discussed further.

Note Accuracy

Means for 5-minute, 6-hour, and 24-hour groups are presented in Figure 6. I compared the note accuracy in participants' performances within each intersession-interval condition using one-way, repeated measures ANOVAs and post hoc one-tailed *t*-tests with appropriate Bonferroni corrections.

There were significant differences among the three note accuracy session means for the 5-minute group, $F(2, 18) = 19.33$, $p < .001$. Post hoc analyses indicate that the mean for Session 1 was significantly higher than the means for Session 2, $p < .001$, and Session 3, $p < .002$, which were not significantly different from one another, $p > .139$.

Likewise, there were significant differences among the three note accuracy session means for the 6-hour group, $F(2, 20) = 11.14$, $p < .002$. Post hoc analyses indicate that the mean for Session 1 was significantly higher than the means for Sessions 2, $p < .014$, and Session 3, $p < .005$, which were not significantly different from one another, $p > .071$.

I found significant differences among the three note accuracy session means for the 24-hour group, $F(1, 6)$[2] $= 6.24$, $p < .048$. Post hoc analyses did not indicate that the mean for the first practice session was significantly higher than the mean for Session 2, $p > .076$, and Session 3, $p > .062$. Differences between means for Sessions 2 and 3 were also not significant, $p > .110$. The lack of observed statistical significance in the post hoc tests can be attributed to the considerable variation associated with this group's performance; clearly, the improvements I observed in this group follow the same trend observed in the other two groups of stable practice learners.

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[2] Corrected df for violation of the sphericity assumption (Lower-bound).

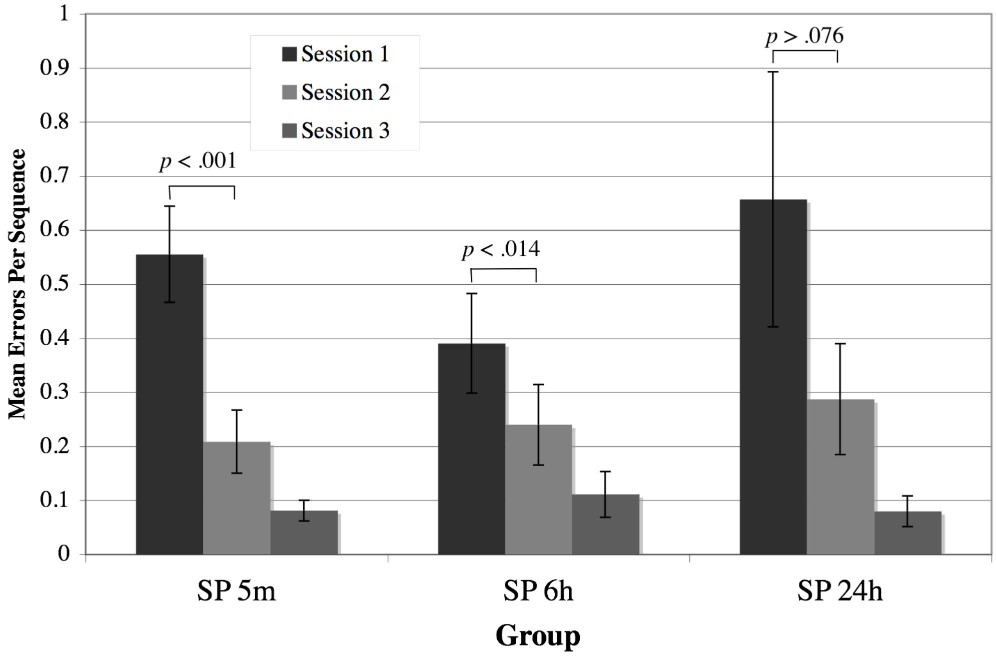

Figure 6: Note accuracy session means for the stable practice experiment. Error bars represent ±1 standard error of the mean.

As was the case in Experiment 1, all of the performance trials in each session were included in the analysis. The fact that data analysis included all information gathered in Session 1 explains, at least in part, the dramatic improvements that occurred between Sessions 1 and 2 in all groups.

Mean data clearly illustrate similar patterns of note accuracy improvement between groups, regardless of how practice was distributed across time. This finding suggests that under externally controlled practice conditions when variation in practice is minimal, improvements in note accuracy are not enhanced by sleep-based consolidation. It is important to note that this is the first experiment that used a controlled number of repetitions in the practice of a sequential keypress task. The resulting pattern of skill improvement is quite different from patterns observed when learners engage in self-regulated practice, which suggests that beneficial effects of memory consolidation may be mediated by the different kinds of practice. Or it may be that the time course of skill improvement under stable practice conditions is different from that of self-regulated practice conditions.

Tempo Accuracy

Means for 5-minute, 6-hour, and 24-hour groups are presented in Figure 7. I compared tempo accuracy in participants' performances within each intersession-interval condition using one-way, repeated measures ANOVAs and post hoc one-tailed *t*-tests with appropriate Bonferroni corrections.

There were significant differences among the three tempo accuracy session means in the 5-minute group, $F(1, 9)$[3] = 6.76, $p < .030$. Post hoc analyses indicate that the mean for Session 1 was significantly higher than the means for Session 2, $p < .052$, and Session 3, $p < .036$, which were not significantly different from one another, $p > .279$.

There were also significant differences among the three tempo accuracy session means in the 6-hour group, $F(2, 20) = 6.27$, $p < .009$. Post hoc analyses indicate that the mean for Session 1 was significantly higher than the means for Session 2, $p < .017$, and Session 3, $p < .043$, which were not significantly different from one another, $p > .500$.

There were significant differences among the three tempo accuracy session means in the 24-hour group, $F(2, 12) = 5.08$, $p < .026$. Post hoc analyses indicate that the difference between Session 1 and 2 means was not significant, $p > .122$, and that the

[3] Corrected df for violation of the sphericity assumption (Lower-bound).

mean for Session 1 was not significantly different from the mean for Session 3, $p > .073$. Sessions 2 and 3 were not significantly different from one another, $p > .219$. Again, the lack of observed statistical significance in the post hoc tests can be attributed to the variation in this group's performance. Trends of skill improvement between sessions are the same as those observed in the 5-minute and 6-hour groups in the stable practice condition.

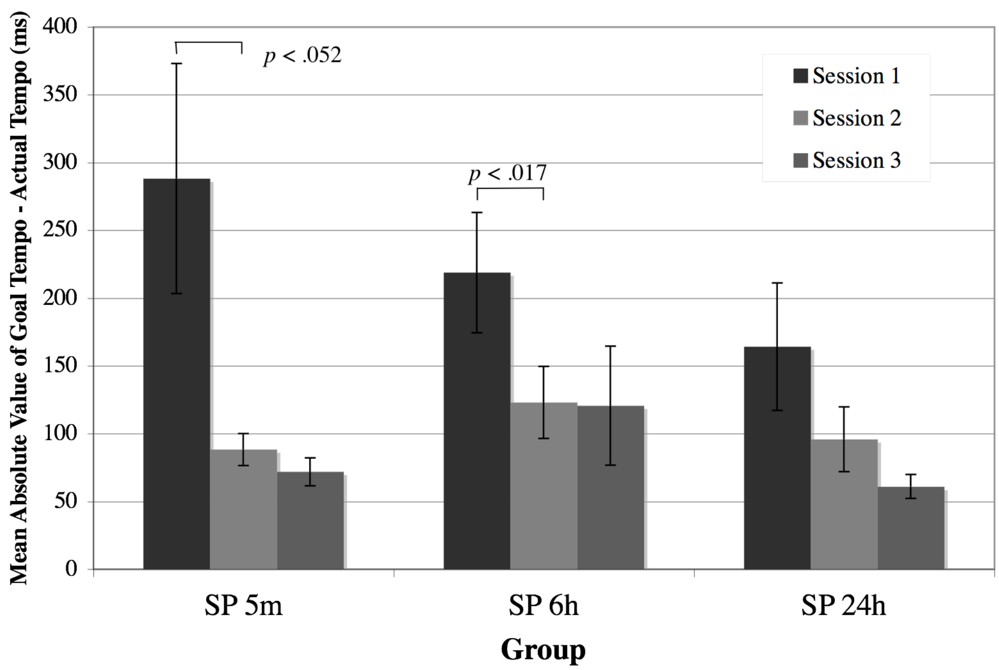

Figure 7: Tempo accuracy session means for the stable practice experiment. Error bars represent ±1 standard error of the mean.

Comparisons among the session means for tempo accuracy reveal that patterns of performance improvement were similar in the three groups; memory consolidation offered no clear performance advantage to participants in the 6- and 24-hour groups over massed practice in the 5-minute group. As observed with note accuracy data, these findings suggest that the beneficial effects of memory consolidation may be mediated by practice conditions, or that under stable practice conditions, skill improvements occur on a different time course than has been observed under self-regulated practice conditions. It may be that the initial stages of consolidation that begin during practice are effective in bringing about skill improvements on a more rapid time course when learners engage in externally controlled practice that includes little variation in the way skills are executed from trial to trial than when they engage in self-regulated practice. These data suggest that improvements in skills learned under systematically controlled and varied practice conditions may not be enhanced by processes of memory consolidation.

There were no significant correlations between note accuracy and tempo accuracy across all sessions for the stable practice condition: Session 1, $r = .197$, $p > .315$; Session 2, $r = .264$, $p > .175$, Session 3, $r = .142$, $p > .470$. In other words, note accuracy performance was unrelated tempo accuracy performance when learners engaged in stable practice of this task.

EXPERIMENT 3: VARIABLE PRACTICE AND MEMORY CONSOLIDATION

Experiment 3 was designed to examine the effects of memory consolidation on procedural skills learned under systematically controlled practice conditions that include variations in speed from trial to trial.

In short, I observed significant enhancements in note accuracy for participants who slept between Sessions 1 and 2. I observed significant improvements in note accuracy performance between Sessions 1 and 3 for the 6-hour group as well. There were no significant tempo accuracy enhancements in any group. A more thorough description of my results follows.

Self-reports of Sleep and Alertness

There were no differences between groups in the amount of sleep participants reported for the night before Session 1, F (2, 24) = .078, $p > .925$. Reported sleep was unrelated to note accuracy data in all sessions: Session 1, $r = .194$, $p > .332$; Session 2, $r = .017$, $p > .964$; Session 3, $r = -.410$, $p > .239$. Likewise, there were no significant correlations between reported sleep and tempo accuracy data: Session 1, $r = .192$, $p > .337$; Session 2, $r = -.108$, $p > .767$; Session 3, $r = -.523$, $p > .121$.

I compared participants' ratings of alertness in each session with corresponding note and tempo accuracy data. There were no relationships between participants' ratings of alertness and note accuracy data in Sessions 1 and 2: Session 1, $r = .324$, $p > .100$; Session 2, $r = .089$, $p > .719$. In Session 3, there was a significant, moderate correlation between ratings of alertness and note accuracy data, $r = .545$, $p < .017$, which indicates that participants who reported greater levels of alertness (represented by lower numbers on the alertness scale) tended to perform with greater note accuracy (represented by a lower error score). There were no significant correlations between ratings of alertness and tempo accuracy in any of the three sessions: Session 1, $r = .213$, $p > .285$; Session 2, $r = .151$, $p > .538$; Session 3, $r = -.014$, $p > .956$. As observed in Experiment 2, the lack of consistent significant correlations between alertness ratings and note or tempo accuracy data make it difficult to draw conclusions from one significant correlation.

Excluded Data

Three participants in the variable practice condition were excluded from this analysis based on the same criteria used in the previous two experiments. Two participants were from the 5-minute group; the third participant excluded from the analysis was from the 6-hour group. Descriptive analysis identified these three as outliers in at least one group session mean; at least two block means were in excess of two standard deviations away from their respective group block means. There were 27 participants included in this analysis (5-minute group, $n = 8$; 6-hour group, $n = 9$; 24-hour group, $n = 10$).

There were problems with the five post-session trials for all of the participants that preclude a meaningful analysis. The data from these trials will not be discussed further.

Note Accuracy

Means for 5-minute, 6-hour, and 24-hour groups are presented in Figure 8. I compared the note accuracy in participants' performances within each intersession-interval condition using one-way, repeated measures ANOVAs and post hoc one-tailed *t*-tests with appropriate Bonferroni corrections.

There were no significant differences among the three note accuracy session means for the 5-minute group, $F(2, 14) = 1.34$, $p > .293$. It should be noted that this group's error rate in the first practice session was much lower than the error rate observed in the other groups, leaving little room for change across practice sessions.

There were significant differences among the three note accuracy session means for the 6-hour group, $F(2, 16) = 5.76$, $p < .014$. Post hoc analyses indicate there were no differences between means for Sessions 1 and 2, $p > .086$, and that the mean for Session 1 was significantly higher than the mean for Session 3, $p < .010$. The means for Sessions 2 and 3 were not significantly different from one another, $p > .500$.

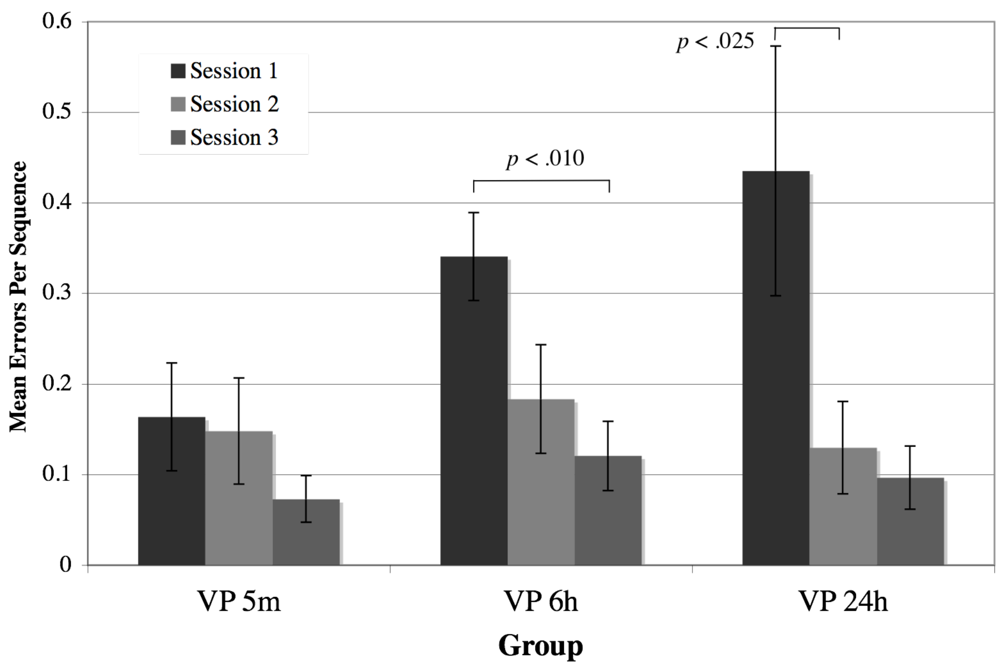

Figure 8: Note accuracy session means for the variable practice experiment. Error bars represent ±1 standard error of the mean.

I also found significant differences among the three note accuracy session means for the 24-hour group, $F(1, 9)^4 = 7.39$, $p < .025$. Post hoc analyses indicate that the mean for Session 1 was significantly higher than the means for Session 2, $p < .025$, and Session 3, $p < .034$. There were no significant differences between means for Sessions 2 and 3, $p > .500$.

Participants in the three groups did not perform similarly at the outset (see Figure 8). As mentioned in Experiment 1, this result is most likely due to a selection variable that I will address later in the document. Between-group differences in Session 1 note accuracy performance do not permit direct comparisons of note accuracy improvements between the 5-minute group and the other two groups. Mean note accuracy data for the 6-hour and 24-hour groups, whose Session 1 performances were similar, demonstrate clear differences in the effects of wake- and sleep-based consolidation. Memory consolidation enhanced Session 2 performance for participants in the 24-hour group, who slept between sessions. Smaller, nonsignificant gains were observed in the 6-hour group, who remained awake between sessions. These results suggest that sleep-based consolidation enhanced Session 2 performance in the 24-hour group, whereas wake-based consolidation did not lead to performance enhancements in the 6-hour group.

Smaller changes in performance were observed between Sessions 2 and 3 for all three groups. It seems that a second night of sleep-based consolidation did not lead to continued performance enhancements between Sessions 2 and 3 in the 24-hour group, nor did wake-based consolidation lead to enhancements between Sessions 2 and 3 in the 6-hour group.

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[4] Corrected df for violation of the sphericity assumption (Lower-bound).

These note accuracy findings are consistent with results reported in Simmons and Duke (2006) and a larger body of research performed with simple motor skills learned under self-regulated practice conditions. Interestingly, these results are inconsistent with the results reported in Experiment 2, in which learners engaged in systematically controlled practice that included minimal variation in the way skills were executed during practice (stable practice).

Tempo Accuracy

Means for 5-minute, 6-hour, and 24-hour groups are presented in Figure 9. I compared participants' performances in terms of tempo accuracy within each intersession-interval condition using one-way, repeated measures ANOVAs.

There were no significant differences among the three tempo accuracy session means for all three groups: 5-minute group, $F(1, 7)$[5] = .936, $p > .365$; 6-hour group, $F(1, 8) = 4.197$, $p > .075$; 24-hour group, $F(1, 9) = 1.933$, $p > .198$. Although changes in tempo accuracy were nonsignificant, comparisons among session means reveal that performance improvements observed were similar in the three groups.

Tempo accuracy findings are consistent with the results of Experiments 1 and 2 in that patterns of performance improvement related to performance speed were similar between groups, whether the speed variable was one of speed capacity (play the sequence as quickly as possible) or speed control (play the sequence at a given tempo). The tempo accuracy findings of Experiment 3 are different from those of Experiments 1 and 2 in that variable practice did not elicit enhancements in performance for all groups in all sessions,

[5] Corrected df for violation of the sphericity assumption (Lower-bound).

whereas self-regulated and stable practice learners demonstrated Session 2 performance enhancements in respective speed variables.

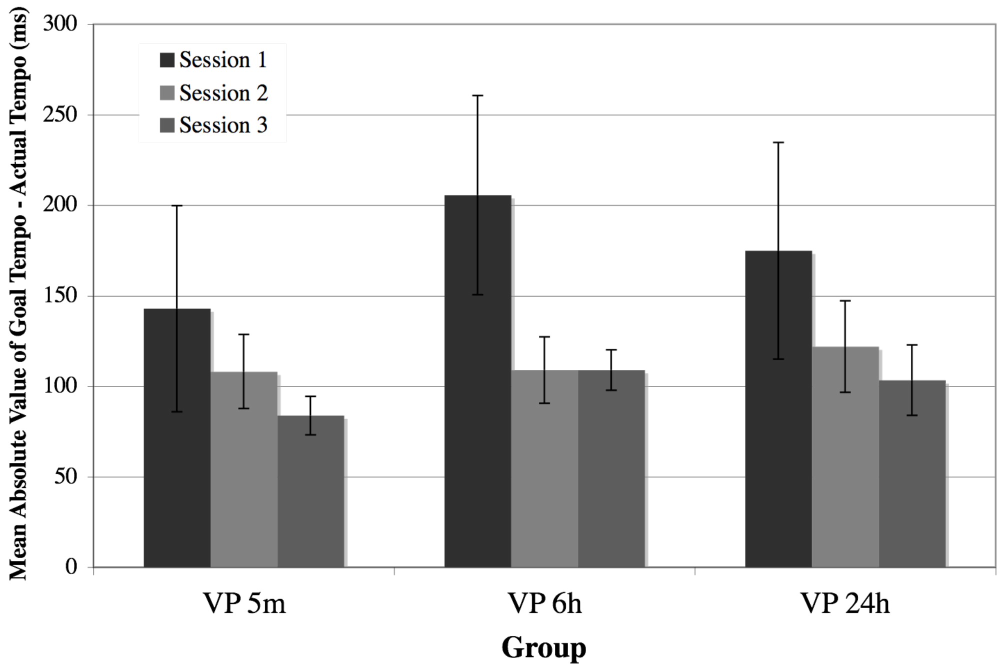

Figure 9: Tempo accuracy session means for the variable practice experiment. Error bars represent ±1 standard error of the mean.

The lack of significant tempo accuracy improvement in any group in the variable practice condition could be related to the demands of performing the skill at speed. Perhaps executing the sequence at M.M. = 52, 72, and 92 in quasi-random order was too difficult for participants to negotiate and inhibited performance enhancements in subsequent sessions. This study is the first to examine the effects of memory consolidation in the context of systematically controlled practice that includes high variability in a skill parameter (speed). As in Experiment 2 (stable practice), these findings suggest that the beneficial effects of memory consolidation may be mediated by the extent to which skill execution is varied during practice and the extent to which practice is externally controlled.

I observed significant correlations between note and tempo accuracy performance in all sessions for all variable practice participants; Session 1, $r = .529$, $p < .006$; Session 2, $r = .725$, $p < .001$; Session 3, $r = .562$, $p < .003$. In other words, participants who played more correct notes tended to match pre-determined tempos more closely than did participants who made more note errors.

SUMMARY OF RESULTS

Experiment 1 (self-regulated practice) replicated the results of Simmons and Duke (2006) by demonstrating that sleep-based consolidation led to significant improvements in note accuracy. The observed changes in performance speed between Sessions 1 and 2 in all groups demonstrated that wake- and sleep-based consolidation led to significant improvements in performance speed. Experiment 1 also showed that a second interval of consolidation (whether wake- or sleep-based) did not lead to note accuracy improvements in Session 3, but did lead to significant improvements in Session 3 performance speed.

Experiments 2 (stable practice) and 3 (variable practice) were the first to examine the relationship between distribution of practice and externally controlled practice that includes variation in performance speed. The results of these two experiments suggest that improvements in skills learned under stable and variable practice conditions do not show the same patterns of improvement as do skills learned under self-regulated speed conditions. The findings of all three experiments provide new insight as to what is known about human learning and memory for procedural skills.

Chapter 5: Discussion

For centuries, musicians have engaged in systematic physical practice to improve performance skills, yet even today the precise relationship between given practice strategies and their effects on the encoding, storage, and recall of procedural memories has not been fully characterized. This study was designed to examine motor memory consolidation and two important variables related to the structure of practice: the organization of variations in practice parameters within practice sessions and the distribution of practice sessions over time.

This investigation is the first to examine wake- and sleep-based memory consolidation in skills learned under externally regulated and varied practice conditions. Perhaps the most important finding of this study is that the time course of motor skill improvements seems to be modified when procedural skills are learned under different rehearsal conditions and when practice sessions are distributed across different intervals of time.

The results discussed below address the following specific questions:

1. Experiment 1: To what extent are complex motor skills affected by wake- and sleep-based consolidation processes in learners with extensive task-related knowledge and moderate levels of task-related skill?
2. Experiment 2: To what extent are consolidation-based enhancements affected by stable practice procedures, in which the speeds of learners' practice trials are externally regulated and practiced in a sequence that includes minimal variation in the way skills are executed from trial to trial?
3. Experiment 3: To what extent are consolidation-based enhancements affected by variable practice procedures, in which the speed of learners' practice trials are

externally regulated and practiced in a sequence that includes maximum variation in the way skills are executed from trial to trial?

NOTE ACCURACY

The results of Experiment 1 are consistent with research conducted using simple motor tasks (Duke & Davis, 2006; Fischer, Hallschmid, Elsner, & Born, 2002; Robertson, Pascual-Leone, & Press, 2004; Walker, Brakefield, Hobson, & Stickgold, 2003; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002; Walker, Brakefield, Seidman et al., 2003) and with research conducted using a keyboard task similar to the one used in this study (Simmons & Duke, 2006). All of this research shows that performance accuracy is enhanced by sleep-based memory consolidation.

The findings in Experiment 2 are inconsistent with those in Experiment 1 and the larger body of neuroscience research described above. The 5-minute and 6-hour groups in the stable practice condition evinced significant note accuracy enhancements between Sessions 1 and 2; improvements in the 24-hour group followed the same trend observed in the other two groups of stable practice learners. Again, the lack of observed statistical significance in this group can be attributed to the large error variation associated with their performances.

Distributing practice over time offered no observable advantage (in terms of performance accuracy) to learners whose practice sessions were separated by 24-hour intervals that included overnight sleep when the speeds of learners' practice trials were externally regulated; similar patterns of performance accuracy improvement were observed in learners whose practice sessions were separated by 5-minute or 6-hour intervals. The results observed in all three stable practice groups suggest that the time course of procedural skill improvements may vary depending on the source of speed regulation (external vs. internal control) and the extent to which practice is varied within sessions.

In Experiment 3, I observed sleep-based consolidation effects consistent with effects observed in Experiment 1, in neuroscience research conducted using simple motor tasks learned under self-regulated practice conditions (Duke & Davis, 2006; Fischer et al., 2002; Robertson et al., 2004; Walker, Brakefield, Hobson et al., 2003; Walker et al., 2002; Walker, Brakefield, Seidman et al., 2003), and in research conducted using a similar keyboard task (Simmons & Duke, 2006). The most interesting finding in this experiment is that sleep-based consolidation effects were observed in learners who engaged in variable practice and who slept between sessions; similar effects were not observed in variable practice learners who remained awake between sessions. This is the first demonstration that learners who practice under externally controlled practice conditions that include a high level of trial-to-trial variability demonstrate sleep-based enhancements in note accuracy similar to those observed in learners who engage in self-regulated practice.

It is interesting to note that the variable practice 6-hour group, who did not demonstrate significant note accuracy enhancements in Session 2, demonstrated enhanced performance by the end of practice (mean performance accuracy was significantly different between Sessions 1 and 3). This result is consistent with results reported in Walker, Brakefield, Seidman et al. (2003), in which continued improvements in accuracy and speed were observed across multiple self-regulated practice sessions that were distributed across one day with no intervening intervals of sleep between sessions. This finding is inconsistent, though, with results observed in the 6-hour self-regulated practice group in this investigation, whose participants did not substantially improve note accuracy performance between multiple practice sessions distributed across one day. It may be that including trial-to-trial variations in practice leads to significant improvements during wake-based consolidation.

In the stable and variable practice 24-hour groups whose practice sessions were spaced across consecutive days, the second night of sleep between Sessions 2 and 3 yielded no significant improvements in note accuracy beyond those obtained by Session 2. The self-regulated 24-hour group reached such high levels of accuracy at the end of Session 2 (approximately .5 errors per block), it would have been unlikely to detect any further improvements.

Comparing patterns of note accuracy improvement between stable and variable practice groups is quite interesting. The 5-minute and 6-hour groups in the stable practice condition demonstrated significant improvements in note accuracy between Sessions 1 and 2, whereas the 24-hour group was the only variable practice group to demonstrate significant note accuracy improvements in Session 2. This difference implicates practice variability as a mediating variable in the consolidation process. Stable practice participants in the 5-minute and 6-hour groups, who negotiated less practice variability from trial to trial than did learners in the variable practice groups (performing all trials at one tempo before practicing the next tempo), obtained significant improvements in note accuracy in Session 2, irrespective of the fact that their intersession interval did not include sleep; however, significant improvements in note accuracy between Sessions 1 and 2 in the variable practice condition were only evident following sleep-based consolidation.

As the data in Figures 4 and 8 clearly show, participants in the self-regulated practice condition did not perform similarly in Session 1, nor did participants in the variable practice condition; therefore, direct comparisons of note accuracy between the 5-

minute groups and the other two groups in those practice conditions are not possible. As mentioned above, comparisons between the three stable practice groups, whose Session 1 performances were similar, revealed no clear differences related to intersession-interval condition.

The Session 1 note accuracy differences between the self-regulated and variable practice conditions may be attributable to the adjustments I made to accommodate participants' schedules during group assignment. In order to fill each group, I accommodated the busiest of the willing participants by assigning them to the 5-minute groups. Of course, the busiest students in a music school are typically those who are in high demand because of their levels of relevant music skills. The schedule adjustments I made, which violated random assignment of conditions, seem to have resulted in the most able participants being assigned the 5-minute rest interval condition. There were fewer reassigned participants in the stable practice 5-minute group, whose Session 1 performance was similar to the other two groups in that practice condition, than there were in the self-regulated and variable practice 5-minute groups. It is important to note that the performances of participants for whom I made schedule adjustments were not markedly better than performances of the other participants in the same groups; rather, it seems that the number of people likely to perform with more skill was increased in the 5-minute rest interval condition as a result of this compromise.

Performance differences observed in Session 1 between 5-minute, 6-hour, and 24-hour groups in both the self-regulated and variable practice conditions are not likely attributable to circadian influences. It does not seem that Session 1 performances were affected by the time of day practice occurred. The 6-hour groups completed Session 1 between 8:00-10:00 AM, the 5-minute groups between 10:00 AM–1:00 PM, and the 24-hour groups between 1:00-4:00 PM. The largest difference in Session 1 scheduling occurred between the 6-hour and 24-hour groups, yet I observed no Session 1 performance differences between those two groups in either practice condition. There is also no evidence of circadian influence on participants' performances in the stable practice condition.

SPEED AND TEMPO ACCURACY

All participants in Experiment 1 evinced improvements in speed between Sessions 1 and 2 irrespective of the time intervals between sessions. The self-regulated 6- and 24-hour groups continued to demonstrate speed enhancements in Session 3, perhaps due to the combination of continued practice and additional intervening consolidation.

These results are consistent with the data reported in studies conducted with simple motor skills (Fischer et al., 2002; Robertson et al., 2004) and music learning tasks (Simmons & Duke, 2006) in that speed enhancements were observed following both wake- and sleep-based consolidation. The participants in the present study, unlike those in Simmons and Duke, were able to significantly and consistently improve performance speed with practice, irrespective of the time intervals interposed between sessions. Changing the task from the melodic-type sequence of notes practiced in Simmons and Duke (2006) to a more unitary musical gesture or flourish facilitated consistent significant improvements in performance speed for all three self-regulated practice groups between Sessions 1 and 2, and for the 6-hour and 24-hour groups between Sessions 2 and 3.

Performance speed is a measure of motor capacity (i.e., playing the sequence as quickly as possible) whereas tempo accuracy is a measure of motor control (i.e., gauging movements in a sequence to match a target tempo). Most memory consolidation research to date has considered motor capacity and not motor control in finger sequence learning. Experiment 1 demonstrated significant improvements in speed (motor capacity) for all self-regulated learners, irrespective of their assigned intersession-interval condition.

Patterns of skill improvement observed in Experiment 2 (stable practice) were similar to those observed in the self-regulated practice condition. Participants in all three stable practice groups demonstrated improved tempo accuracy in Session 2, irrespective of the intersession intervals. Improvements between Sessions 1 and 2 were significant in the 5-minute and 6-hour groups and approached significance in the 24-hour group. Session means for the 24-hour group clearly show a skill improvement pattern similar to the other two groups; the lack of significance observed is attributable to the large variation observed in this group's data and the resulting low power of the statistical tests. The fact that there were no significant differences in tempo accuracy between performances in Sessions 2 and 3 in any group in the stable practice condition suggests that wake- and sleep-based consolidation offered no clear advantage to learners in the 6- and 24-hour groups. Perhaps continued enhancements in motor control require more time and practice to become evident, or perhaps the extent of improvements obtained in a regulated practice procedure are such that consolidation-based enhancements are not evident in learners' behavior for this dependent measure.

Although all groups in Experiment 3 improved across practice sessions, none of the observed differences between sessions was significant. Perhaps the trial-to-trial adjustments required in the variable practice procedure, in particular the size and accompanying physical demands of the speed adjustments, added a level of complexity to the task that learners could not overcome. In other words, variable practice as implemented in this task may have overloaded learners to the extent that significant tempo accuracy enhancements were not possible in this short time frame. It is notable that almost no learners ever mastered the skill at the fastest performance speed; this may indicate that those who could not play the sequence at tempo remained focused on maintaining or increasing note accuracy at the expense of improvements in tempo accuracy.

It is quite possible that the time course of skill improvements in the variable practice condition would have been different if task complexity, learner sophistication, and the extent of variability included in practice had been better matched. Perhaps the extent to which I varied practice tempos was too great; in other words, performing randomly ordered trials at M.M. = 52, 72, and 92 demanded motor skill capacity (i.e., performing fast enough to match M.M. = 92) and control (i.e., negotiating a much slower tempo, M.M. = 52) that these participants could not manage in this short a time frame. As I mentioned in the discussion of the note accuracy results, stable practice participants, who had to contend with less practice variability than did variable practice participants, improved in terms of tempo accuracy between Sessions 1 and 2.

Recall that studies of procedural memory consolidation in finger sequence learning has measured motor capacity (i.e., how fast skills can be executed), not motor control (i.e., controlling movement speed). Perhaps the differences I obtained in these three practice conditions are attributable in part to the fact that motor capacity improvements develop on a different time course than do improvements in motor control.

CORRELATIONS BETWEEN NOTE ACCURACY AND SPEED VARIABLES

The significant, moderate, positive correlations between note accuracy and speed (self-regulated practice condition) in Sessions 1 and 2 and between note accuracy and tempo accuracy (variable practice condition) in all three sessions indicate that improvements in note accuracy and speed tended to develop concurrently. The lack of relationship between note accuracy and speed in Session 3 in the self-regulated condition is attributable to fact that these participants reached a ceiling for note accuracy by the end of Session 2.

The same relationships between note accuracy and tempo accuracy were not observed in the stable practice condition. This result is interesting in that improvements in one variable did not occur at the expense of the other (i.e., matching tempos more closely did not consistently elicit more errors, and vice versa), nor did improvements in one variable consistently coincide with improvements in the other variable. I find it difficult to interpret why correlations between note accuracy and speed variables were observed in self-regulated and variable practice conditions and not observed in the stable practice condition.

GENERAL DISCUSSION

The most unique contributions of this investigation come from the introduction of externally controlled practice conditions that include systematic variations in target performance speeds. The focus of the remaining discussion addresses the contributions made by the results observed in these practice conditions.

There are several important differences between this study and previous work that demonstrates memory consolidation effects. As was the case in Experiment 1, other neuroscience research conducted with simple motor skills, and research conducted by Duke and Davis (2006) and Simmons and Duke (2006) required learners to attend to only one judgment of correctness during practice (self-evaluation of keypress accuracy). Experiments 2 and 3 in this investigation required learners to attend to judgments of note *and* tempo accuracy, which increased the complexity of processing demands during practice. Learners were forced to work toward achieving two defined goals (correct sequence of finger movements and accurate movement speed). In this investigation and in Simmons and Duke (2006), I and the other proctors observed during testing that learners—all skilled musicians—typically focused on achieving note accuracy before attending to attaining prescribed goal speeds. In other words, it was more important to participants that the notes be correct than that they be played at the target tempo, a priority in keeping with the practice habits of most skilled performers in music.

The observation that participants in this study and in Simmons and Duke (2006) tended to strive for note accuracy at the expense of speed is attributable to the fact that they were provided relevant auditory feedback (musicians heard every trial they performed on the keyboard) throughout practice. Perhaps without concurrent auditory feedback, musicians may be more likely to strive to reach accuracy goals and speed goals simultaneously. Processing concurrent feedback certainly complicates motor skill acquisition, even in the acquisition of simple motor skills (Schmidt & Wulf, 1997). It is interesting to note that in self-regulated and variable practice conditions (Experiments 1 and 3), participants still demonstrated significant sleep-based improvements in note accuracy despite the fact that they were processing concurrent auditory feedback that undoubtedly influenced their performance across practice.

One aspect of the variable and stable condition comparisons is the similarity in the error rates between learners practicing on stable and variable schedules. This finding is contrary to a great deal of motor learning research (Giuffrida, Shea, & Fairbrother, 2002; Li & Wright, 2000; Pollock & Lee, 1997; Shea, Kohl, & Indermill, 1990; Shea, Lai, Wright, Immink, & Black, 2001; Simon & Bjork, 2001; Tsutsui, Lee, & Hodges, 1998; Young, Cohen, & Husak, 1993) which demonstrates that variable practice leads to more error during acquisition and better performance at retest than does stable practice. The results I observed in initial practice *and* in skill recall do not show such a trend.

Difficulties Inherent in Distributed and Variable Practice

As I attempted to randomly assign participants to the nine groups in this study, I found that some people were either reluctant to participate or simply could not work participation into their schedules when assigned to the distributed practice conditions (6- and 24-hour groups). Similar situations have been observed before by Baddeley and Longman (1978), who reported that participants preferred massed practice over distributed practice, mostly for practical reasons of convenience.

A review by Lee and Wishart (2005) discussed that distributed practice is not as efficient as massed practice in terms of the total elapsed time from the onset of practice to reaching criterion. I see this somewhat differently. If distributed practice enhances performance more than massed practice, less time can be spent in the act of practicing, even though more time (over the course of days) is required to reach a given performance goal.

Lee and Wishart (2005) also suggest that variable practice may be undesirable because of the large error rates typically observed in initial stages of practice; those error rates cause learners to make metacognitive judgments that learning is not progressing during acquisition. This negative attitude could limit students' motivation to practice. I did not observe substantially different error rates between stable and variable practice conditions in this experiment, but this may be an important point to consider in future studies.

QUESTIONS RESULTING FROM THIS INVESTIGATION

In future investigations, I would like to structure experiments that allow for direct statistical comparisons of stable and variable practice by including an equal number of trials at each tempo in all three practice sessions. This may require the addition of a practice block before the first session that would comprise 15 self-regulated trials. Allowing participants one self-regulated block at the beginning of practice may allow them to acclimate to the sequence more effectively before practice variability is introduced.

Testing experienced learners performing authentic music skills presents special challenges in research of this type, in which the optimal balance between task complexity, learner sophistication, and the extent of variation in practice is somewhat difficult to achieve. In future experiments, I intend to pre-test participants performing similar keyboard skills before assigning practice conditions; this will allow more control for the wide variability in participants' performance skills by matching between groups.

Perhaps a more effective measure of motor control needs to be developed as well. Future investigations may be directed at narrowing the range of predetermined tempos that participants are required to perform. Reducing the demands of motor capacity may have a direct effect on participants' ability to negotiate contextual interference in practice, potentially making consolidation effects on motor control skills more evident.

Motor learning research clearly demonstrates that providing learners with visual and auditory feedback affects learning. In this investigation and in Simmons and Duke (2006), processing concurrent auditory feedback during practice seems to exert a considerable effect on the choices musicians make during practice. If musicians were not given auditory feedback during practice and could no longer hear errors in note accuracy, would that impact the choices they make during practice? Might they prioritize note accuracy, speed, and tempo accuracy differently than musicians who can hear their performances?

Future investigations that focus on manipulating the frequency and specificity of visual KR in motor control investigations (displaying computer feedback in terms of tempo accuracy) may also affect musicians' ability to improve performance. In this study, the computer program offered specific tempo accuracy feedback (to the tenth of a metronome marking) to participants in the stable and variable practice conditions after every trial. Many participants responded with audible frustration when they would get very close to the tempo they were shooting for yet be off by a fraction of a metronome marking. Offering less specific feedback, referred to as *bandwidth KR* in motor learning literature, may focus learners' attention more on consistency in skill execution and less on matching tempos to at a level that is very exact. Some motor learning researchers have suggested that constant KR facilitates complex skill learning (del Rey & Shewokis, 1993; Guadagnoli & Lee, 2004), whereas others have proposed that learners engaged in variable practice are overloaded by processing KR after every trial, and that reducing KR frequency under variable practice schedules makes movements more stable (Lai & Shea, 1998). Clearly, more investigation is needed to determine the optimal frequency of KR in complex skill learning.

CONCLUSIONS

These experiments confirm and elaborate what is known about complex motor skill learning under self-regulated practice conditions by demonstrating sleep-based consolidation effects on note accuracy and time-based consolidation effects on speed in the context of music performance. Perhaps the most important finding of this investigation is that memories for skills learned under different practice conditions seem to develop on a time course that is affected by the structure of practice. When learners engage in practice that is externally controlled and includes either minimal speed variation or trial-to-trial variations in performance speed, patterns of skill improvement following intervals of memory consolidation are different from those observed following self-regulated practice.

It is interesting to speculate how the behavioral effects of memory consolidation can be directly applied to optimize music learning. Perhaps new music tasks are best learned with intervening intervals of sleep between their introduction and recall in later practice. Distributing practice across time that allows consolidation to stabilize and enhance procedural memories may even increase the efficiency of musicians' practice time. Although these ideas are interesting to contemplate, their verification requires considerable additional research in the context of music skills.

Appendix A

	Session 1			Sessions 2 and 3		
Practice Condition	Block 1	Block 2	Block 3	Block 1	Block 2	Block 3
Self-regulated	Free to vary speed at will			Free to vary speed at will		
Stable	M.M. = 52	M.M. = 92	M.M. = 72	M.M. = 72	M.M. = 92	M.M. = 52
Variable	M.M. = 52	M.M. by trial = 72, 52, 92, 72, 92, 52, 92, 52, 72, 72, 92, 52, 72, 92, 52	M.M. by trial = 72, 92, 52, 92, 52, 52, 72, 92, 72, 52, 72, 92, 92, 52, 72	M.M. by trial = 52, 92, 72, 92, 92, 72, 52, 72, 92, 72, 52, 92, 72, 52, 52	M.M. by trial = 72, 72, 52, 92, 92, 52, 72, 52, 72, 92, 52, 92, 72, 92, 52	M.M. by trial = 92, 52, 72, 52, 92, 72, 92, 52, 92, 72, 52, 72, 52, 92, 72

Appendix B

APPROVED BY IRB ON: 04/28/2005 ***EXPIRES ON: 04/28/2006***

CONSENT FORM

The Effects of Memory Consolidation and Practice Variability on Musicians' Retention of a Motor Sequence

IRB PROTOCOL # 2005-04-0006

Conducted By: Amy L. Simmons
Center for Music Learning, School of Music, The University of Texas at Austin
Telephone: (512) 471-2466
e-mail: amysimmons@mail.utexas.edu

You are being asked to participate in a research study. This form provides you with information about the study. The person in charge of this research will also describe this study to you and answer all of your questions. Please read the information below and ask questions about anything you do not understand before deciding whether or not to take part. Your participation is entirely voluntary and you can refuse to participate without penalty or loss of benefits to which you are otherwise entitled. You can stop your participation at any time by simply telling the researcher.

The purpose of this study is to examine the effects of memory consolidation and practice variability on memory of a motor sequence.

If you agree to be in this study, we will ask you to do the following things:

- Learn a simple motor sequence on a keyboard during the training session (20 min);
- Perform a sequence during two retest sessions on a subsequent day and time (20 min);
- Refrain from consuming drugs, alcohol, and caffeine 24 hr prior to <u>and</u> during your participation.

Total estimated time to participate in study is 1 hour.

Risks and Benefits:

- The risk associated with this study is no greater than everyday life.
- Other than monetary compensation, there are no benefits for participation in this study.

Confidentiality:

- training and retest sessions will be taped;
- data will be coded so that no personally identifying information is visible on them;
- data storage disks will be kept in a secure place (e.g., a locked file cabinet in the investigator's office);
- data storage disks will be reviewed only for research purposes by the investigator and her associates;
- disks will be retained for possible future analysis.

Compensation:

- You will be compensated in the amount of $12.00 for your participation.

The **records** of this study will be stored securely and kept private. Authorized persons from The University of Texas at Austin, members of the Institutional Review Board, and (study sponsors, if any) have the legal right to review your research records and will protect the **confidentiality** of those records to the extent permitted by law. All publications will exclude any information that will make it possible to identify you as a subject.

Contacts and Questions:

If you have any questions about the study please ask now. If you have questions later or want additional information, call the researcher conducting the study. Her name, phone number, and e-mail address are at the top of this page.

If you have questions about your rights as a research participant, please contact Clarke A. Burnham, Ph.D., Chair, The University of Texas at Austin Institutional Review Board for the Protection of Human Subjects, (512) 232-4383.

You will be given a copy of this information to keep for your records.

Statement of Consent:

I have read the above information and have sufficient information to make a decision about participating in this study. I consent to participate in the study.

Signature:____ Date: __________________

____ Date: ___________________
Signature of Person Obtaining Consent

Signature of Investigator:_______________________________ Date: __________________

Appendix C

Self-regulated Practice, 24-hour Group

Session 1:

Name: Subject #:

How do you feel right now?

Are you a music major? Y N

Which is your dominant hand? R L Gender: M F

Principal Instrument: Years of Study:

What other instruments have you studied?

For how long?

Finger Independence Training (+3 years of study): Y N

Have you ever taken piano lessons? Y N How long? At what age?

How many semesters of class piano have you completed?

How much sleep did you get last night? Well? Restlessly?

Is that a typical amount of sleep for you?

Have you had any caffeine, alcohol, or drugs in the last 12 hours? Y N

If yes, how much of what?

Notes:

Session 2:

How do you feel right now?

Have you had any caffeine, alcohol, or drugs since we met last time? Y N

If yes, how much of what?

Did you play a music instrument yesterday after we met?

If so, which instrument and for how long?

Did you play a music instrument before our meeting today?

If so, which instrument and for how long?

How much sleep did you get last night? Well Restlessly

Notes:

Session 3:

How do you feel right now?

Have you had any caffeine, alcohol, or drugs since we met last time? Y N

If yes, how much of what?

Did you play a music instrument yesterday after we met?

If so, which instrument and for how long?

Did you play a music instrument before our meeting today?

If so, which instrument and for how long?

How much sleep did you get last night? Well Restlessly

Notes:

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Vita

Amy Lynn Simmons was born in Hampton, Virginia on July 17, 1974. She is the daughter of Rose R. Condon and Harry G. Forbes, Jr., and she has two sisters, Jenny R. Forbes and Sally E. Grassmuck. As a military dependent, Amy had the opportunity to live in many places as a child. She completed junior high and high school in San Antonio, Texas, and then earned a B.M. in Music Studies from The University of Texas at Austin in 1997. Amy taught middle school band for four years at Forestwood Middle School in Lewisville, Texas. During that time, she also played professional oboe with the Camerata Chamber Winds in the Dallas area. In 2001, she moved back to Austin to begin graduate study at The University of Texas. She married Roger E. Simmons in January 2002, and finished her M.M. in Music and Human Learning in May 2003. After completing her PhD coursework, Amy accepted a position as an Assistant Professor of Music Education at The University of Texas at San Antonio, where she continues to teach today. Amy still plays oboe professionally in the Austin and San Antonio areas. Roger and Amy have a remarkable daughter, Abbie, and are expecting a son in the summer of 2007.

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