MaGKeyS: A haptic guidance keyboard system for facilitating sensorimotor training and rehabilitation

by

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Abstract

The Magnetic Guidance Keyboard System (MaGKeyS) embodies a new haptic guidance technology designed to facilitate sensorimotor training and rehabilitation. MaGKeyS works by employing active magnetic force to guide finger pressing movements during sensorimotor learning that involves sequential key presses, such as playing the piano. By combining this haptic guidance with an audiovisual learning paradigm, we have created a core technology with possible applications to such diverse fields as musical training, physical rehabilitation, and scientific investigation of sensorimotor learning.

Two embodiments of this new technology were realized in this thesis. The first embodiment, the MaGKeyS Prototype, is a 5-key acrylic USB keyboard designed for a stationary right hand. A set of three behavioral experiments were executed to investigate the manner in which haptic guidance, via the MaGKeyS Prototype, facilitates rhythmic motor learning. In particular, the experiments examined the independent effects of haptic guidance on ordinal learning, which is the order of notes in a sequence, and temporal learning, which is the order of timing variations in a rhythmic sequence. A transfer test and 24-hour retention test were also administered. Our results provide conclusive evidence that haptic guidance can facilitate learning the ordinal pattern of a keypress sequence. Furthermore, our results suggest that the advantage gained with haptic guidance can both transfer to learning a new rhythmic sequence, as well as extend to a demonstrable advantage a day later.

The second embodiment, the MaGKeyS Trainer Piano, is an upright piano in which the keyboard has been modified and outfitted with electromagnets in a manner similar to the MaGKeyS Prototype. The Trainer Piano helps to teach by "feel" by providing an experience in which the user feels his or her fingers being pulled down into the correct piano keystrokes as the piano plays itself.

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Chapter 1

Introduction

"A process cannot be understood by stopping it. Understanding must move with the flow of the process, must join it and flow with it."

- First Law of Mentat

Dune, by Frank Herbet (1965)

1.1 Overview

This thesis describes the design, fabrication and testing of a new sensorimotor training technology for teaching sequential human finger movements. The Magnetic Guidance Keyboard System (*MaGKeyS*) uses magnetic force to control the pressing movements of the fingers over small distances (< 1 inch), similar to the range found in keyboard key presses. This is accomplished by using an electromagnet located underneath the key of a keyboard to dynamically control the movement of a permanent magnet attached to the fingertip, positioned above the key (Fig. 1-1). Employing such a method to teach movements is more commonly referred to as *haptic guidance*, meaning that the user is guided through the target motion via their sense of proprioception and touch. In the present scenario, haptic guidance is achieved by dynamically controlling the user's key presses as they are engaged in an audiovisual behavioral learning paradigm (Fig. 1-2).

In this thesis project, two embodiments of MaGKeyS were realized. The first embodiment, the MaGKeyS Prototype, is a 5-key USB electromagnetic keyboard (Ch. 3). This

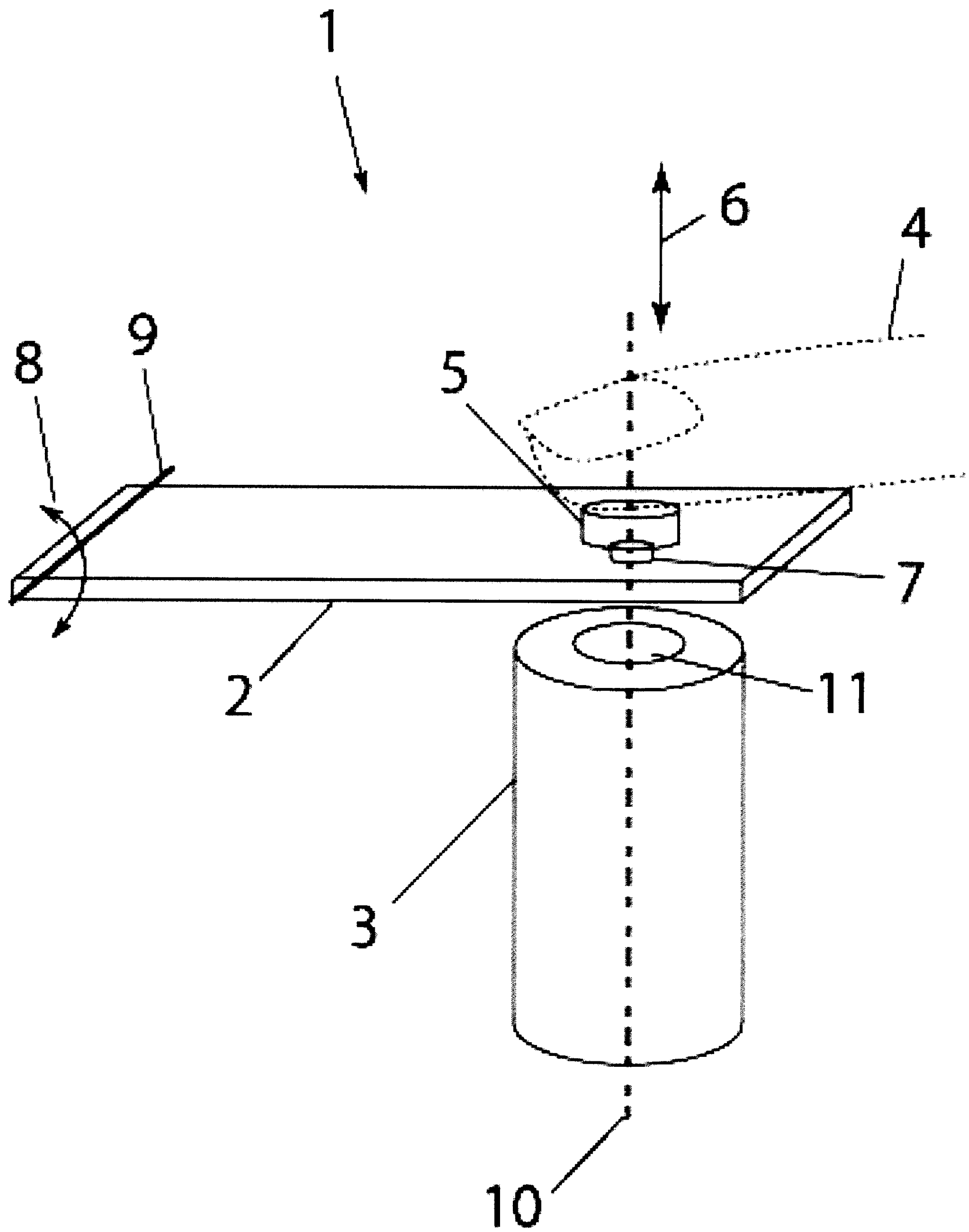

Figure 1-1: Schematic of keypress actuation paradigm (1). The key (2) is positioned some distance above an electromagnet (3). The finger (4), with a permanent magnet (5) attached to the fingertip, rests on the key along the center axis (10) of the electromagnet. A smaller permanent magnet (7) is used to position the finger correctly. When the electromagnet is powered with current, the resulting magnetic force can attract or repel the finger in the direction (6). The attraction of the finger causes the key to rotate (8) about its hinge (9).

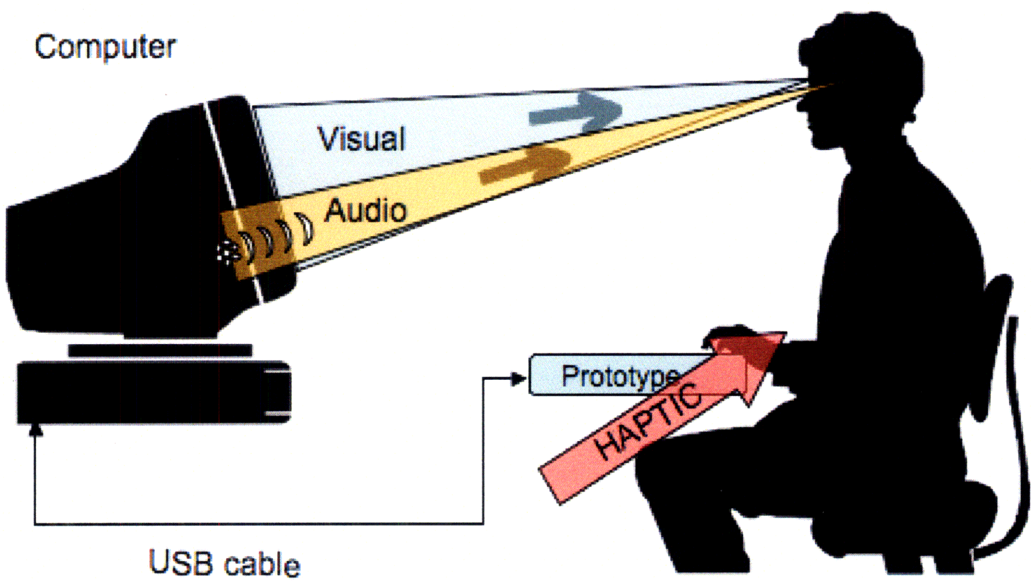

Figure 1-2: An illustration of haptic guidance through the use of the prototype USB electromagnetic keyboard. Haptic information is provided to the user, in addition to audio and visual information, to guide the user in a behavioral learning paradigm.

keyboard was developed specifically for use in behavioral experiments to validate the efficacy of MaGKeyS technology. A set of three behavioral experiments (Ch. 4) was executed to investigate the manner in which haptic guidance, via the MaGKeyS Prototype, facilitates rhythmic motor learning. In particular, the experiments examined the independent effects of haptic guidance on ordinal learning, which is the order of notes in a sequence, and temporal learning, which is the order of timing variations in a rhythmic sequence.

The second embodiment, the MaGKeyS Trainer Piano (Ch. 5), is an upright piano in which the keyboard has been modified and outfitted with electromagnets in a manner similar to the MaGKeyS Prototype. The Trainer Piano helps to teach by "feel" by providing an experience in which the user feels his or her fingers being pulled down into the correct piano keystrokes as the piano plays itself.

1.2 Motivation

The overarching motivation for this work comes primarily from the author's view that it is possible to engineer human-computer interfaces that can that significantly facilitate sensorimotor learning. This view is supported by three rapidly growing bodies of research and development:

Physical devices for facilitating motor learning & rehabilitation The past decade has seen significant growth in the development of physical devices for motor training and rehabilitation. The majority of research has come from the field of Rehabilitative Robotics, which generally employs large haptic robotic devices to assist stroke and other neurologically-damaged patients in the rehabilitation of motor movements.

Neuroscience of motor learning We have also seen significant advances in understanding the brain processes mediating human motor learning, largely due to advances in imaging techniques such as fMRI and PET. This breakthrough in cognitive neuroscience has allowed researchers to start asking questions about complex human motor movements, such as the rhythmic movements often found in musical performance. Recent work in this field has begun to elucidate the brain networks involved in different types of sequential rhythmic performance.

Neuroscience of music perception and performance A third and overarching motivation for this work is music. Music has come into increasing popularity with scientists and clinicians as both a vehicle for studying the perceptual and motor faculties of the human body, as well as a method for rehabilitating the neural system. Combined with recent commercial applications of sensorimotor-engaging musical activities, it is starting to become clear that music holds an incredible amount of potential as a vehicle for training and rehabilitating the sensorimotor system.

1.3 Specific Aims & Significance

The goal of this thesis is to take an initial idea of a new technology, and develop both a embodiment platform for scientific validation as well as an embodiment platform for commercial application. The specific aims developed to facilitate the accomplishment of this goal are as follows:

- Demonstrate the embodiment of *MaGKeyS* through the design and fabrication of a prototype electromagnetic keyboard.
- Conduct a set of behavioral experiments to validate the efficacy of MaGKeyS in teaching rhythmic motor movements.
- Demonstrate the design and implementation of MaGKeyS technology in a potential commercial application, the MaGKeyS Trainer Piano.

This work is significant in that it introduces a novel paradigm for training the human sensorimotor system: haptic guidance via actuated keypresses on an electromagnetic keyboard. The combination of engineering and science present in this work is an appropriate embodiment of MIT's motto, *Mens et Manus*.

1.4 Organization

This thesis is divided into four chapters. Chapter 2 covers the background for this work. Chapter 3 covers the design, fabrication and operation of the MaGKeyS Prototype. Chapter 4 covers the three behavioral experiments conducted with the MaGKeyS Prototype. Chapter 5 covers the work on the MaGKeyS Trainer Piano, the first application of MaGKeyS technology to a real-world device.

Chapter 2

Background

The following section covers the background areas for this work. First is an overview of the motor skill acquisition literature, covering the dominant paradigms within that field. The second section is work related to physical devices for sensorimotor learning and rehabilitation. This includes both human methods and robotic methods in training and physical therapy. The third section discusses the neuroscience of rhythmic sensorimotor learning. This section covers recent work in the field of neuroscience investigating how humans execute rhythmic motor sequences. The final section discusses music, its recent prominence in neuroscience as a means for studying perception and action in humans, as well as its role in recent commercial gaming products, and its future role as a stimulus vehicle for driving sensorimotor training and rehabilitation in humans.

2.1 Motor skill acquisition

The study of motor skill acquisition has seen significant development in the past half century. Here, I present a brief overview of some of the major themes in motor learning research during this period[1].

Feedback The role of feedback has been crucial to the study of motor learning. Feedback has been viewed as necessary to the ongoing control of movement as far as back as the time of Woodworth (1899) [6]. Feedback can be divided into two broad categories [5]. *Inherent*

[1]For more in-depth reviews of the motor learning literature spanning the last three decades, the reader is directed to Adams (1987) [1], Newell (1991) [2], Abernethy & Sparrow (1992) [3], and Newell (2001) [4], as well as Schmidt & Lee (2005) [5] for a textbook.

feedback refers to information the subject receives through his or her own sensory channels about the movement. *Augmented feedback*, on the other hand, refers to information provided about the performance that is supplemental to inherent feedback. Two important categories of augmented feedback relevant to the discussion are *knowledge of results* (KR) and *knowledge of performance* (KP). KR refers to postmovement feedback about the outcome of the movement, such as "You hit the target on the bull's-eye," while KP refers to information about the movement pattern, such as "Your wrist was too tight."

Power law The study of motor skill acquisition initially developed as a branch of experimental psychology. One of the early attempts to characterize motor learning was with Snoddy (1926) [7], who demonstrated that performance time in a motor task tends to decrease with practice as a function of a power law. This finding was replicated for a number of different motor tasks, one of the most notable being Crossman's (1959) demonstration of the reduction in production time for cigar makers making 10,000,000 cigars over a seven year period [8]. The general applicability of the power law for practice over a diverse range of performance tasks has naturally led some to view the power law as a general law of motor learning [9, 10].

Fitts' theory of stages One of the early theorists in the domain of motor learning was Fitts (1964), who proposed a theory of learning stages [11, 12]. Fitts' three phases of learning were as follows: the *cognitive phase* involved the initial understanding of the task requirements and how to evaluate task performance. This phase is exploratory in nature and is often where the most dramatic gains are seen. The role of KR is often very important during this stage. The *associative phase* lasts for a period of many days to weeks, during which the baseline skills acquired from the *cognitive phase* are refined. The final stage is the *autonomous phase*, which takes place on a much longer timescale, often months, during which the acquired motor skills becomes automatic and require little attentional resource to complete.

Adams' closed-loop theory The first theory that incorporated the role of feedback in both the control and learning of movement was Adams' (1971) closed-loop theory of motor learning [13]. Adams' theory was unique in that it proposed that normal movement was controlled by a two-state memory mechanism that continuously compared the arriving afferent information about the movement with a stored "image" of the correctness of that movement. Adams called the first state the *memory trace*, which served as an internal "image" of the desired movement. The memory trace is akin to choosing to initiate a movement, such as picking up a cup. The second state was the *perceptual trace*, which served as an "image" of the correctness of execution of the initiated movement. The *perceptual trace* is fundamental in evaluating the movement. Adams hypothesized that the *perceptual trace* develops in the early stages of learning through the use of KR feedback, but at later stages of motor learning becomes KR independent. Adams' theory sparked a number of studies in the mid-70's revolving around the importance of KR for learning and the characteristics of the error correction mechanism [14, 15, 16, 17]. Adams' theory was ultimately undermined by its inability to account for the control of rapid movements [18, 3]

Keele's open-loop theory Like many other branches of psychology, the study of motor skill acquisition was influenced significantly by the information processing theories of the 1950s and 1960s. As humans began to invent and develop electronic frameworks to store and process information, much of the science behind the investigation of human motor skill acquisition mimicked, albeit indirectly, these contemporaneous views and frameworks. The computer metaphor, as a means of describing the operation of the human being, was readily apparent in the work of Keele [19] and his formalization of the motor program. Keele defined the motor program as a set of centrally stored commands that allowed for the execution of a movement pattern without the need to rely upon sensory feedback. Keele's theory was an open-loop theory; it did not account for feedback in shaping the movement once initiated. This view of motor skill acquisition was able to account for a limited subset of motor actions, but eventually ran into problems.

Both Adams' and Keele's theories relied heavily on the concept of centrally-stored action-specific commands for the execution of movement. In Adams's theory, a *memory trace* and *perceptual trace* existed as one-to-one mappings for all possible movements. Similarly, in Keele's theory, motor commands were stored for every movement. Two theoretical problems emerged with these models of motor learning. The first problem dealt with the issue of storage. Given the vast range of possible movements of the human body, how could the central nervous system (CNS) store all these representations? The second problem dealt with the issue of novelty; if only specific commands were stored, then how did the motor system generalize to account for learning new movements, or even perturbing an existing movement?

Schmidt's schema theory These issues were dealt with directly by Schmidt's (1975) schema theory for motor learning [20]. Schmidt retained Adams' independent memory state mechanisms, but applied the concept of the schema to these mechanisms, giving them a generalized construct (one-to-many mappings). Schema theory is based around the idea that task-specific experiences are driven by abstracted 'rules' that dictate the relationships between the specific motor commands, sensory input, environmental conditions and resultant motor output. Instead of specific motor commands being stored in the CNS, Schmidt postulated that schema 'rules' governing a class of movements were stored in the CNS. This allowed Schmidt to account for the storage and novelty problems that had plagued Adams and Keele. One of the more interesting developments from investigations of the schema theory was the concept of practice variability. Since the schema rules were generalized rules governing sets of actions, Schmidt proposed that the rules would be stronger if a range of movement variations were experienced during practice. This gave rise to the hypothesis that motor retention and transfer would be enhanced by variability of practice, because under such training the schema rules would form around a wider variety of possible movement actions (for reviews of variable practice see [21, 22]).

The motor skill acquisition theories discussed above are all prescriptive in the sense that each theory holds at its core a centralist representational scheme for prescribing a movement or set of rules to meet particular task constraints. As discussed by Abernethy & Sparrow (1992) [3], the first full-scale paradigm shift[2] within the field of motor learning occurred arounded the beginning of the 1980s, with the development of the 'ecological' approach to action. The ecological approach, which is also called the 'actions systems', 'action theory' or 'dynamical systems' approach to motor learning, is represented by a collection of theories that are grounded in the belief that movement kinematics are *not* stored centrally, but rather arise as an emergent property of the underlying dynamics of the motor system.

According to Newell [2], the ecological approach appears to have evolved from three intellectual precursors. The first of these is Bernstein (1967), who characterized the coor-

[2]Kuhn coined the term 'paradigm shift' in his seminal work *The Structure of Scientific Revolutions* [23] to describe events and time periods within fields of scientific work in which the basic assumptions of a particular field are changed dramatically.

dination of movement as finding an optimal solution for the particular motor task being accomplished [24]. Bernstein saw practice, and thus learning, as the repeated execution of finding a solution, rather than repeatedly executing an internally stored program or set of rules. The second intellectual precursor comes from Gibson (1979) [25], whose seminal work in describing an ecological approach for visual perception helped to provide a framework for viewing the perceptual-motor workspace and the informational rules about the environment. The third precursor was the growing body of physiologist-based work in describing movement control in terms of the physical/dynamical properties of muscles, including the work of Bizzi [26, 27], Kelso [28, 29] and Turvey[30, 31, 32].

The emergence of the ecological approach to motor learning is particularly interesting because it parallels similar paradigmatic shifts within other fields of science that were occurring around the same time. Notable among these is the paradigm shift in cognitive science from cognitivism/representationism to enactive cognitive science[33, 34]. One of the interesting questions approached within enactive cognitive science deals with the nature of "information" transferred during communication. Whereas prior representationist accounts of communication would posit that an internal representation of the "information" is transmitted from from one agent to another (i.e. "sender" to "receiver"), enactive cognitive science postulates that no "information" exists at all; instead, all that exists is a particular structural coupling within one organism (what we call "knowledge"), that is then enacted within a mutual coupling with another organism (the communicative medium, i.e. physical proximity, electronic communication, etc.) such that the "receiver" experiences the enacted structural coupling of the "sender" and thus forms their own internal structural coupling (they "receive" the "information"). What is interesting to point out in enactive cognitive theory is that "information" never exists apart from an embodied structural coupling, but is *always* intrinsically linked to the individual's structural coupling. When the "receiver" in the scenario above proceeds to communicate with another person (consequently becoming the new "sender"), the "information" that they transmit is necessarily influenced by their own internal structural coupling. In this view, it is argued that "information" does not ever exist as a separate entity, but is instead always embodied within a structural coupling, and therefore always influenced by the particular structural coupling of the individual. Each individual has a unique perspective, because it turns out that our knowledge and abilities are intrinsically linked to our individual physical makeups (structural couplings).

Considering these recent emergent theories, what can be said about the role of information[3] in shaping motor skill acquisition? Newell [2] presents us with a very nice perspective on this issue: "Information in the ecological approach to perception and action is interpreted as the means via which the learner channels the mapping of information and movement dynamics in the perceptual-motor workspace in a way consistent with the task demands." Newell suggests that both information about the invariant properties of the environment, as well as augmented information, can be continuously employed to "channel the search" through an operator's perceptual-motor workspace to find an optimal solution for their particular task. One possible form of providing augmented information to "channel the search" is through the use of engineered devices. In the next section, the discussion turns to the recent development of devices that facilitate sensorimotor training and rehabilitation.

2.2 Devices for facilitating sensorimotor learning and rehabilitation

Rehabilitative Robotics The past ten years (1998-2008) has seen explosive growth in physical devices designed for facilitating sensorimotor learning and rehabilitation, largely in the field of Rehabilitative Robotics [35]. Work in this field traces its roots back to motor adaptation studies using force feedback devices. A standard experimental setup for these types of experiments involves a two degree of freedom (DOF) robotic arm. This robotic arm allowed for movement in the horizontal plane, and was used to measure how subjects trace out arm reaching paths on a horizontal surface. Subjects learned to move the robotic arm through a target path in the horizontal plane while under the influence of a perturbing force. After the subject adapted to the perturbing force field, the field was removed and the subsequent path execution served as a measure of the amount of adaptation the motor system had incorporated to correct for the perturbing force [36, 37, 38]. A more recent study used this paradigm to implicitly teach subjects a prechosen movement, and concluded that training under the influence of external force fields in such a manner holds a great deal of potential for teaching motor skills and for facilitating rehabilitation for brain injury patients [39].

[3]Despite our discussion on the enactive cognitive science perspective that "information" in fact does not exist as a separate entity, we still use the term as an effective placeholder for describing the communicative process.

The first significant rehabilitative robotic device was the MIT-MANUS, developed by Neville Hogan and colleagues at MIT [40]. The initial MIT-MANUS was a 2-DOF robotic arm, similar to those used in the force feedback studies. Hogan *et al.* conducted a number of controlled randomized studies on acute hemiparetic patients (stroke patients with slight weakness on one side of the body) usually beginning within a month after their first stroke [41, 42, 43]. In these studies, the patients were split into two groups; a robotic group would receive treatment with the MIT-MANUS, while the control group received "sham" robotic therapy. Compared with the control group, the robotic group's motor function for their shoulder and elbow was significantly larger after treatment, as assessed by the Fugl-Meyer (FM) motor score, a common clinical motor-impairment scale. These improvements were maintained over time; a three-year follow up study still demonstrated a significant difference between the two groups[44]. A follow up study also demonstrated this effect for chronic stroke patients[45].

These initial studies into the use of haptic robots for physical rehabilitation ignited a wave of development of similar devices. Numerous devices for rehabilitating the upper extremity have been developed [46, 47, 48, 49], and an equal amount of effort has been devoted towards robotic device for rehabilitating the lower extremity, particularly gait training [50, 51, 52, 53, 54, 55, 56]

Devices for the Hand and Wrist Rehabilitative Robotics has also begun to make inroads into devices for the hand and wrist. The MIT-MANUS group recently began using a wrist rehabilitation device in their upper extremity rehabilitation setup [57, 58]. This device facilitates rehabilitation of the wrist along three degrees-of-freedom: abduction-adduction; flexion-extension; and pronation-supination (wrist rotation). The addition of the wrist component to the MIT-MANUS allows for rehabilitation and training of the shoulder, elbow and wrist. Initial results of 36 stroke survivors from an ongoing clinical trial indicated significant improvements, as assessed by FM score. These subjects were split into two groups and engaged in 12 weeks of rehabilitation; one group of subjects received six weeks of robot-delivered wrist therapy followed by six weeks of robot-delivered shoulder-and-elbow therapy, while another group received six weeks of should-and-elbow therapy followed by six weeks of wrist training. The device is currently employed in a clinical trial enrolling 200 stroke survivors, the results of which are yet to be published.

Another rehabilitative robotic device for the hand is The Haptic Knob [59], a 2-DOF robotic interface constructed to adapt to different hand sizes. The Haptic Knob allows for different haptic interfaces through interchangeable doorknob-like inserts, allowing for the device to retrain a variety of basic hand functions, such as opening and closing of the hand, object grasping and pinching, and coordinated grasping and wrist rotation. Preliminary data collected on the device with chronic stroke patients (N=3) indicated that the patients were able to use the device, but did not present any conclusive evidence of the device's efficacy as a rehabilitative tool.

Another device, The Hand Wrist Assistive Rehabilitation Device ('HWARD') [60], is a 3-DOF device allowing for flexion/extension of the four fingers about the MCP joint, flexion/extension of the thumb at the MCP joint, and flexion/extension of the wrist. Takahashi *et al.* [60] studied the effects of this device on a subject pool of 13 chronic stroke patients, assessing both the ability of the device to help retrain motor function, and the dosage of such therapy, and found significant gains in hand function by all subjects, and even more so with the group in which the therapeutic dosage was highest.

In general, a significant amount of effort has been directed at development of devices for upper and lower extremity rehabilitation, with more recent work aimed at devices for the hand and wrist.

Haptic Guidance A few studies have also applied these robotic devices to explicitly teach trajectory movements to normal subjects. As discussed before, *haptic guidance* refers to a paradigm in which the device physically guides the user through the correct motions, thus providing a proprioceptive representation of the desired movement. Haptic guidance is generally used to describe the application of such devices in a normal training environment, whereas rehabilitative robotics generally refers to the implementation of such devices in a rehabilitative setting.

One of the first of these studies was conducted by Feygin *et al.* (2002) [61], who used a 3-D robotic haptic arm to train users in executing unique 3-D trajectories. Using the PHANTOM^{TM}, a commercially-available desktop haptic interface device (SensAble Technologies, Woburn, MA), three training methods were studied: visual training (V), in which the subject watched the end of the robotic arm move through the target motion, haptic guidance (H), in which subject grasped the end of the robotic arm and was guided through the target motion while their vision of the robotic arm was blocked, and haptic plus vision (H+V), in which the subject watched the robotic arm as they were guided through the target motion. Feygin *et al.* found that visual training resulted in better performance for learning the trajectory shape, but that haptic guidance facilitated learning the correct timing, or temporal aspect, of the trajectory.

Liu *et al.* [62] re-examined the Feygin *et al.* result by running a similar experiment in which the target trajectories were less complex and more similar to motions found in a rehabilitative context. The target 3-D paths were designed to engage a novel muscle activation pattern while remaining a simple multi-joint movement. Liu *et al.* only tested two types of training conditions from the Feygin *et al.* study: visual training (V) and haptic plus visual training (H+V). Their results indicated that both forms of training improved short-term recall of a novel path, but that haptic guidance did not provide any significant improvement in performance.

In both of the above studies, no advantageous effect of haptic guidance was observed for learning the correct trajectory shape. However, each of these studies examined haptic guidance for relatively random motor movements, specifically complex 3-D trajectories. While the Liu *et al.* study attempted to use target motions that were more similar to those found in a rehabilitative context, it could be argued that those patterns were still random, in that they had no functional significance to the subject. Very recently, a study looked at haptic guidance in facilitating learning to write Arabic and Japanese-inspired letters [63]. In this study, the investigators again used the PHANTOM^{TM}to study two different modes of "teaching". In one mode, the device was used to convey position information to the user, while in the other mode, the device was used to convey force information. Results from their visuo-manual tracking experiment indicate that haptic guidance does not provide any benefit for spatial tracking, but did provide benefit for learning kinematic control of specific force variations over space and time.

Conclusions about guidance Despite the large body of devices designed for facilitating sensorimotor rehabilitation, the evidence for haptic guidance is not overtly strong. In the haptic guidance studies discussed above, all experimental conditions involved either visual or haptic (or both) learning. Perhaps the 3-D visuomotor tasks used in these studies are not the most appropriate task for elucidating the potential effects of haptic guidance. The primary function of the visual system is the observation and recognition of objects and their arrangements in 3-D space. Therefore, it could be possible in the above studies that the information presented by the haptic sense, while relative to the task, did not provide any significant advantage over the native abilities of the visual system in accomplishing the task.

Nevertheless, there is still an intuitive notion about the possible efficacy of haptic guidance, probably in part due to the large role that instructors have in presenting augmented information to students. In fact, the concept of physical guidance in training and rehabilitation is not new [5]. In sports, coaches frequently physically guide a player's movements during practice. Similarly, in music, instructors often physically guide the movements of the student in order to help them achieve the right sound. If these forms of physical guidance are so native to our learning environment, then why is there such little support of haptic guidance? As covered later, the emergence of new haptic devices, specifically those incorporating music, might provide a unique avenue into the design of future haptic devices, as well as provide the right medium for haptic guidance to be effective.

2.3 Neuroscience of rhythmic sensorimotor learning

Knowledge of the brain circuits underlying motor skill learning and performance has advanced significantly in recent years [64]. Advances in imaging techniques, such as functional magnetic resonance imaging (fMRI) and positron emission topography (PET), have made it possible to observe the changes in neural activity while subjects are engaged in a perceptual-motor task. Since these imaging techniques only work when the subject's head is stabilized, most of these experiments are designed around finger movement tasks that can be executed without moving the head. This has lead to a body of investigations looking at the neural basis of rhythmic perception and production.

Sakai *et al.* (1999) [65] were some of the first to conduct a controlled study of rhythmic perception in normal human subjects (much of the prior work was on brain-damaged patients). Subjects performed a short-term memory task for a seven note sequence, in which the ratio of temporal intervals (the relative timing between notes) was either metrical (1:2:3, 1:2:4) or nonmetrical (1:2.5:3.5)[4]. Using fMRI, subjects were scanned during a 10-second

[4]Metrical rhythms refer to rhythms in which the time intervals are integer multiples of a base interval. For an interval size of 1 = 250ms, 1:2:3 corresponds to a rhythm comprising intervals of size 250ms, 500ms, and

window between being presented with the sequence and playing it back. Separate patterns of brain activation were found; the 1:2:3 and 1:2:4 rhythms elicited a network of activity in the left premotor and parietal areas, as well in the right cerebellar anterior lobe; the 1:2.5:3.5 rhythm elicited activity across the right prefrontal, premotor and parietal areas along with the bilateral cerebellar posterior lobe. This finding seems to indicate that distinct neural representations exist for metrical and nonmetrical rhythms. Specifically, nonmetrical rhythms elicit bilateral cerebellar activation and prefrontal activation, in addition to the premotor and parietal activation seen during metrical rhythms.

Ramnani & Passingham (2001) [69] used PET to study changes in brain activity while learning a rhythm. They used a variant of the frequently-used Serial Reaction Time (SRT) experimental paradigm [70], in which the reaction time (RT), the interval between stimulus presentation and user response, is taken as an index of performance. Under the SRT paradigm, learning of a sequential pattern is accompanied by a decrease in RT. In Ramnani & Passsingham's behavioral experiment, the visual stimulus indicated which of four buttons to press, and was presented either in a rhythmic manner, or at random time intervals. By correlating their imaging data with the RT data, they could infer the areas active during rhythm learning. Their results showed increased activity in the posterior lateral cerebellum, intraparietal and medial parietal cortex, presupplementary motor area (pre-SMA) and lateral premotor cortex.

Sakai, Ramnani & Passingham (2002) [71] conducted a study in which they attempted to distinguish the brain regions underlying temporal and ordinal sequence learning. In a sequence, the temporal property refers to the time intervals between successive notes, while the ordinal property refers to the order of note identities. By randomizing the ordinal and temporal characteristics of their stimulus set, Sakai *et al.* created a set of stimuli that targeted these two types of learning independently. Using PET, they found distinct regions underlying temporal and ordinal learning. In particular, learning the order of finger movements was associated with increased activity in the right intraparietal sulcus and medial parietal cortex, while learning a temporal sequence was associated with increased activity in the lateral cerebellum. Under stimulus conditions that involved both temporal

750 ms, while 1:2:4 characterizes a rhythm comprising intervals of 250ms, 500ms, and 1000ms. Nonmetrical rhythms, on the other hand, are characterized by temporal intervals that are not integer multiples of a base. For 1 = 250ms, 1:2.5:3.5 characterizes a rhythm comprising intervals 250ms, 625ms, and 875ms. Refer to [66, 67, 68] for more reading.

and ordinal learning, increased activation was found in the frontal lobe, particularly in the mid-dorsolateral prefrontal cortex and premotor areas. Since this condition was the only condition that constituted explicit learning of a particular motor sequence, involving both temporal and ordinal learning, Sakai *et al.* suggested that the frontal lobe might mediate "action-oriented" integration of timing and ordinal information.

Ullen & Bengtsson (2003) [72, 73] also investigated differences between temporal and ordinal learning[5]. In addition to many of the same areas reported above, they found activation in the basal ganglia during ordinal learning. A more recent study looking at beat perception also found increased activity in the basal ganglia. Grahn & Brett (2007) [74] measured subjects' brain activity with fMRI during tasks in which the subjects tapped out beats of different rhythmic complexity. Their results indicated increased activity in the basal ganglia and supplementary motor area (SMA) during rhythms which were more more metrically salient (they induced a stronger beat). Very recently, Zatorre and colleagues[75] used fMRI to investigate the neural substrates underlying performance of rhythmic sequences of increasing complexity by both musicians and nonmusicians. Their results indicated that musicians recruited a greater amount of prefrontal cortex than nonmusicians.

In general, these studies seem to indicate that different aspects of rhythmic performance are mediated by different areas of the brain. Increasing rhythmic complexity is mediated by increased activity in the frontal lobe and cerebellum, in addition to the premotor, motor and parietal areas normally recruited for simple rhythmic movements. The basal ganglia have also been implicated in being activated during metrically salient rhythms in which a strong underlying "beat" is perceived. Finally, increased musical ability, as seen in musicians, seems to be mediated by the ability to recruit larger areas of frontal cortex.

2.4 Music

Music is beginning to emerge as a rich tool for neuroscientists studying the brain processes underlying perception, performance, memory and emotion [76, 75]. Music not only serves as a way to study complex motor functions such as rhythmic ability, but also as a tool for understanding the neural substrates underlying autobiographical memories [77, 78]. In a

[5] The **ordinal** property of a sequence is the order of notes within the sequence, such as a sequence comprising the notes A-B-C-B-A. The **temporal** property of a sequence is the order of temporal intervals between successive elements, such as a sequence comprising notes of length 250ms, 250ms, 500ms, 750ms, 250ms.

recent study, Janata *et al.* looked at the networks of brain structures activated when a listener hears an excerpt of popular music that is highly associated with a past memory. Subjects were played 30-sec excerpts from songs that were on the Billboard Top 100 Pop and R & B lists during the years in which they were between 7 and 19 years old. Using fMRI and an extensive survey system, their results revealed a significantly larger network of activated brain regions when the musical excerpts had strong autobiographical salience (the song is highly associated with a particular memory), compared with musical excerpts with weak autobiographical salience.

Music is also gaining prominence as a rehabilitative tool. Melodic Intonation Therapy (MIT) is a music-based therapy that has been used with patients who have Broca's aphasia, a post-stroke speech disorder characterized by a loss in speech production abilities while maintaining fairly normal speech comprehension abilities. One of the peculiar presentations of Broca's aphasia is that these patients, while having lost their ability to speak, can often times retain the ability to sing. MIT is a technique that engages the patient's ability to sing as a means of retraining speech function. Patients start off by singing phrases, and then gradually transition the singing into normal speech. In the first study that attempted to verify the efficacy of MIT [79], two aphasic patients with similar baseline speech impairments received separate therapies; one patient received 40 treatment sessions of MIT (1.5 hours/session, 5 days/week), while the other patient received 40 treatment sessions of a control intervention, Speech Repetition Therapy (SRT). Results at the post-40 session assessment revealed significant speech ability improvements for both subjects (as assessed by a battery of speech production measures designed to quantitatively assess spontaneous speech). The MIT-treated patient, however, showed greater improvement on all outcomes than the SRT-treated patient. The effect of MIT was beneficial enough that the SRT-treated patient was then transitioned to receiving MIT therpay.

Music and haptics Several researchers have also begun to look at the role of haptic feedback and guidance in musical controllers and musical performance. Sile O' Modrain looked at the role of haptic feedback in a variety of different virtual musical performance contexts. First, she used a haptic display called the *Moose* to look at the effect of haptic feedback on performance accuracy with the theremin, an electronic instrument that is played by positioning one's hands in 3-D space relative to two radio antennas[80]. The *Moose* is a two-axis haptic interface designed to provide computer access to blind persons by transmitting 2-D haptic feedback. Results indicated that haptic feedback facilitated more accurate control of the theremin. A second set of experiments used a virtual model of a string and bow, similar to a violin, to investigate how important the sense of friction is to correct bow performance.[81]. The results from this study concluded that while haptic feedback can improve a player's initial learning of a virtual instrument, any haptic device intended to simulate the feel of a real instrument would have to be of high quality if it is to facilitate skill transfer from the virtual to the real domain.

More recently, Graham Grindlay developed two haptic musical devices for teaching percussive rhythm: FielDrum and HAGUS [82]. FielDrum uses an electromagnet underneath a drumhead to control the movement of a permanent magnet attached the end of a drumstick, similar to MaGKeyS. A magnetic shield was placed over the top of the drum to control the region of movement of the drumtick tip to an area close to the drum head. Due to the rapid attenuation of magnetic flux strength with distance[6] this was necessary to ensure that subsequent magnetic attractions would be actuated by the drumstick. The second system, HAGUS, used a servo motor and optical encoder attached to the shaft of a drumstick to provide precise haptic guidance and measurement for playing temporal sequences. A pilot study investigating temporal learning was run with this device. It was found that the addition of haptic guidance to audio-based learning produced nearly a 20% error reduction for sequence recall.

Another area that has seen the marriage of music and haptic is in the field of commercial video gaming. These recent developments, combined with the prominence of music-based video and interactive gaming devices (Guitar Hero™, Dance Dance Revolution™, Nintendo Wii™), are positioning music as a unique entity with multiple applications for studying, training and rehabilitating the human sensorimotor system.

Discussion: Music as a vehicle for sensorimotor training and rehabilitation Once again we visit Newell's idea of using augmented feedback to "channel the search" throughout the perceptual-motor space. Given the prevalence of human physical guidance in our culture, it seems only natural that more devices will be developed to facilitate motor learning via haptic guidance. Two such devices are presented in this thesis. However, de-

[6]Coincidentally, electromagnetic radiation from a point source exhibits an inverse-square relationship, which is an example of a power law.

vices alone will not create a rehabilitation paradigm; equally important is the "information" that is used to facilitate the experiential coupling. We have to ask ourselves, *what* are we instructing patients to do when they train or rehabilitate with a haptic guidance robotic device? Whether it is performance or passively listening, music has the power to recruit large regions of neural activity, making it a perfect vehicle for driving sensorimotor training and rehabilitation. In many ways, this should not be surprising; the cultural evolution of music is deeply intertwined with dance. Furthermore, this emerging role of music and haptics is readily demonstrated in the recent success of music-based haptic gaming devices such as Guitar Hero^{TM}, Dance Dance Revolution^{TM}, and Nintendo Wii^{TM}. Perhaps as more devices emerge, we will begin to see music as the primary vehicle for facilitating sensorimotor training and rehabilitation.

Chapter 3

Prototype Design, Fabrication and Operation

The following chapter provides an overview of the development of the MaGKeyS Prototype electromagnetic keyboard. The initial embodiment of the prototype is described, followed by an operational description, hardware description, and software description of the final version of the prototype used in the behavioral experiments.

3.1 Initial Embodiment

The initial embodiment of MaGKeyS was a precursor to the current version of the MaGKeyS Prototype (Fig. 3-1). An acrylic keyboard housing was used, but the keys were circular buttons. Driver circuitry was implemented on a breadboard, and the system was controlled by a script running in MATLAB. This early prototype was able to demonstrate electromagnetic attraction of a permanent magnet above the key, but not much beyond that. The keys lacked enough ergonomic stability to be consistently useful, and MATLAB proved a poor software environment for prototyping this system.

Experience with the initial prototype uncovered a number of issues that were taken into consideration in subsequent work. The first of these was the issue of portability. It was desirable to design a keyboard that could be taken outside of the laboratory and demonstrated with a laptop. The second issue was cross-platform compatibility. It was necessary to do software develop in an environment where the program could run on either Windows or Macintosh operating system platforms. The two constraints were solved with our choice of communication and software. For communication, two protocols were considered: USB and MIDI. USB was ultimately chosen given it's ubiquity, speed and universal design. For software, the Python programming language was chosen as the development environment, given its relatively ease of use for rapid prototyping, as well as its cross-platform compatibility.

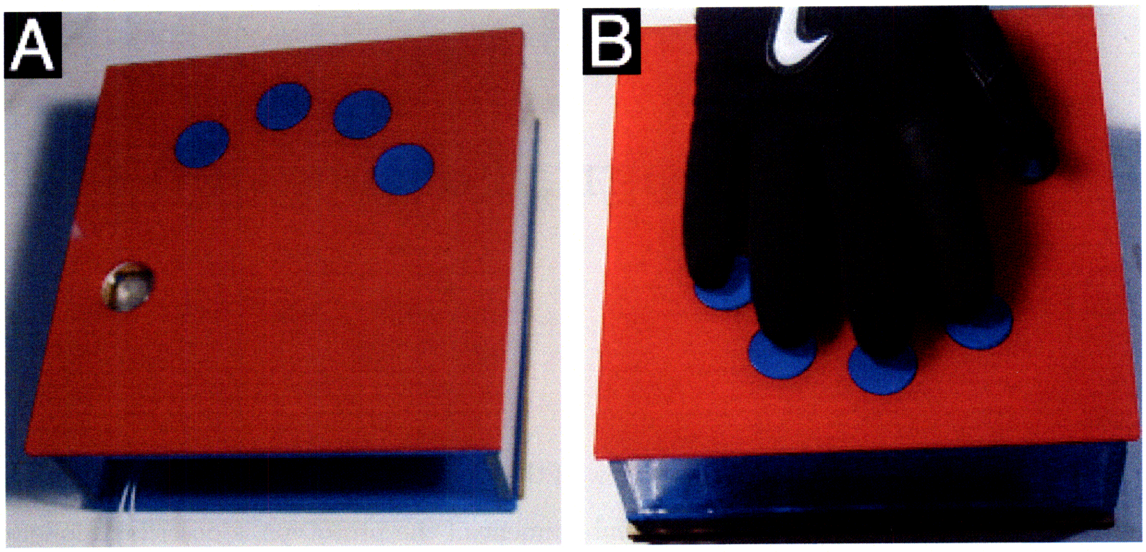

Figure 3-1: Photograph of early prototype design.

3.2 Operational Description

Figure 3-2 shows a block diagram of the system hardware. The main components are the host computer system and the electromagnetic keyboard. In our case, we used a Mac Pro desktop computer (Apple Computers) for the host computer.

Communication between the computer and keyboard is achieved via USB, through a commercially available USB prototype board which also houses an ATMEGA microprocessor. The software running on the computer issues commands via the serial bus to the keyboard. Firmware running on the keyboard microprocessor then interprets the incoming commands from the computer into control signals for the H-bridge driver chips, which control the electromagnets. When a key is depressed, a switch located underneath the key encoded the keypresses, which are then translated into commands by the microprocessor which then sends a signal up the USB to the computer, where incoming key presses are logged as data.

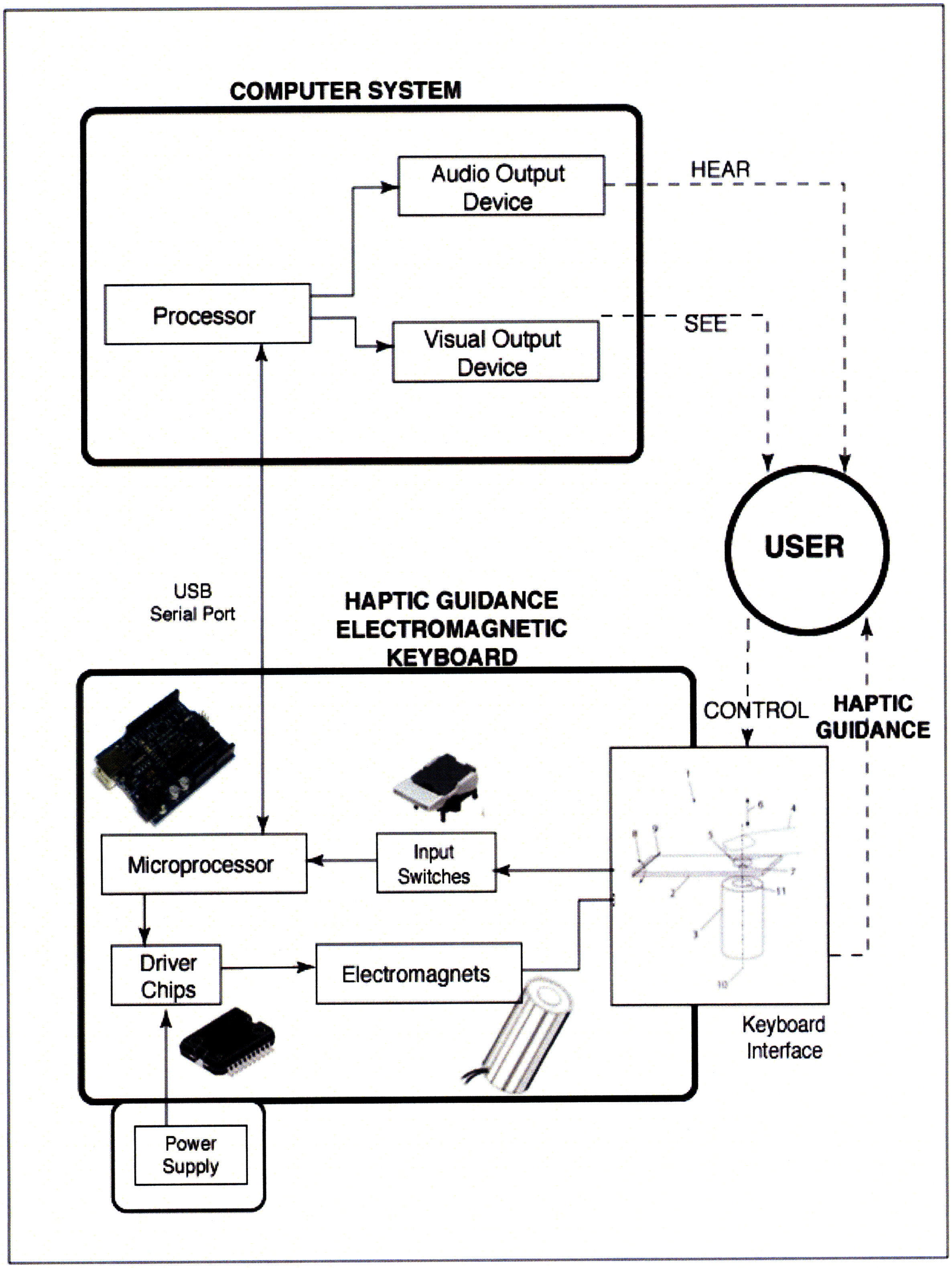

Figure 3-2: Block diagram of complete system, including host computer and electromagnetic keyboard. See text for description.

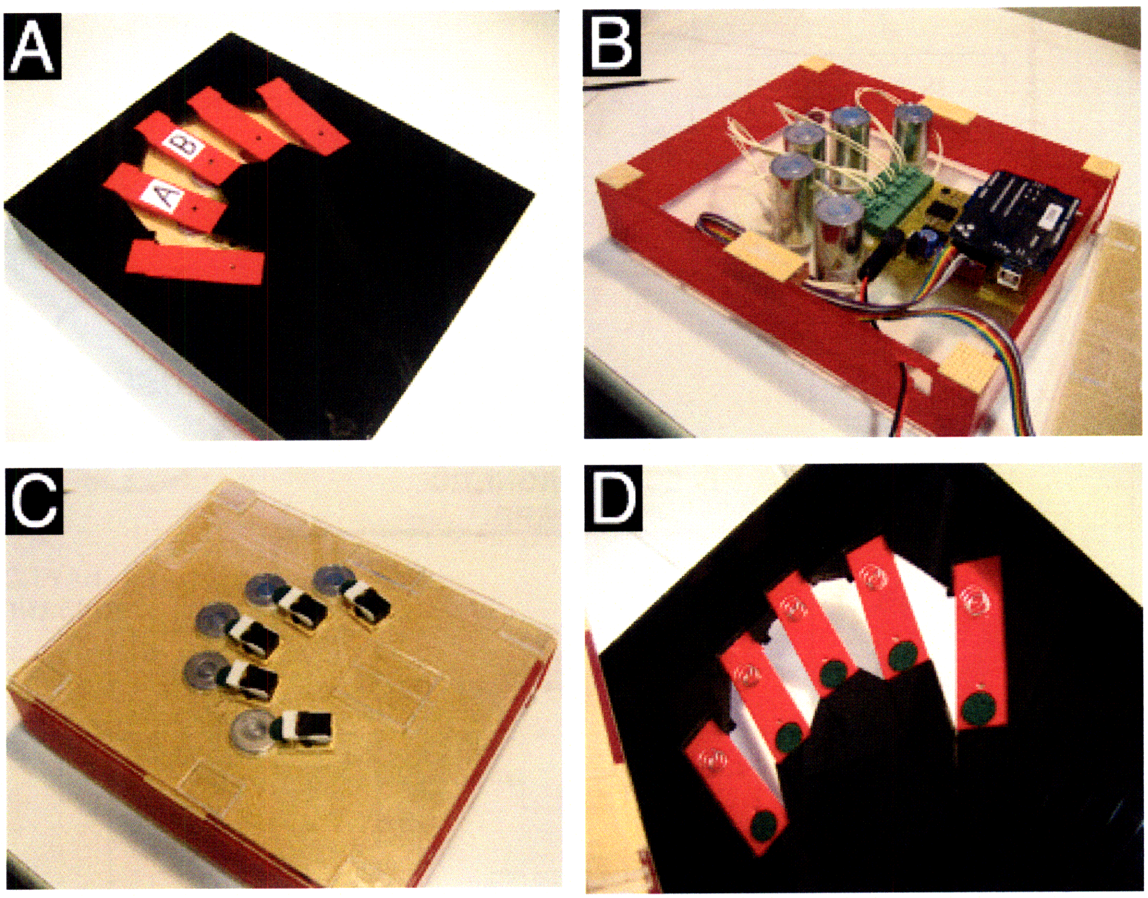

Figure 3-3: Photograph of prototype keyboard constructions. Panel A shows top view of electromagnetic keyboard. Panel B shows base layer, electromagnets and electrical circuitry. Panel C shows the switches layer. Panel D shows underside of keys layer, with springs and felt padding on each key.

3.3 Hardware Description

Keyboard Housing The electromagnet keyboard (Fig. 3-3) is an acrylic box measuring 24.5 cm x 18 cm X 6 cm (LxWxH). The housing and keys are all cut from 1/8" sheets of acrylic, designed using the drafting program Corel Draw, and fabricated on a Laser Cutter. The keyboard contains three layers: a housing layer, switches layer, and keys layer. The housing layer comprises the base and sides, and contains the electromagnets and driver/communications circuitry. The switches layer press fits into the housing layer, and contains the input switches and wiring. The keys layer press fits over the bottom two layers, and contains the hinges and keys. The top two layers were designed such that the key rested 1 cm above the electromagnet, a distance suitable to produce a comfortable keypress stroke.

Keys Figure 3-3 shows the keyboard from the top. The arrangement of the keys was adapted from human hand measurements found in [83]. The keys hinged on the end away from the fingers. The hinges were 19mm watchband parts. Small neodymium permanent magnets (1/8" dia. x 1/16" height) are embedded in the keys along the vertical axis running through the core of the electromagnets. These magnets serve to help guide the fingers of the hand in resting at the correct location, above the center axis of the electromagnet, such that the amount of magnetic force would be constant for each finger. The top layer is designed such that the keys hinge at the distal end of the keyboard, with the proximal end of the keys resting on the ALPS™ switches. Additionally, springs were glued to the underside of each key to prevent unintended keypresses. Felt padding was used dampen the feel and sound of the keypresses.

USB Microcontroller Board We used a single commercially available USB microcontroller board to handle all operations on the keyboard. This included receiving control signals from the computer and translating them into control signals for the driver chips, as well as reading in switch keypresses and sending them back to the computer.

The board has 12 Digital I/O pins, and 6 Analog Input pins, as well as providing +5V, +9V and Ground pins. The central processor on the board is an Atmel Atmega 168.

PCB & Driver Chips The driver chips for the electromagnets were 5.0A H-bridge chips (#MC33887, Freescale Semiconductor). The chips were housed on a printed circuit board

(PCB) designed by the author using Eagle software. The schematic of this board is shown in Figure 3-4. This board housed the 5 driver chips and connected to the USB board. A 5A, 30V power supply (Pyramid, model # PS-32LAB) also connected to the PCB to provide power to the electromagnets.

Electromagnets Electromagnets measured 25mm in diameter and 49 mm in height, with an impedance of 7.1 , and consisted of approximately 825 turns of 26 AWG wire. (www.electromechanicsonline, Van Nuys, California).

Input Switches The switches we used were manufactured by ALPS Electric Co. The part number is SPPY121500.

3.4 Software Description

Software was programmed using the Python programming language, with heavy use of the PyGame toolkit. Figure 3-5 shows a flowchart of the software. In idle mode, the software awaits a keypress to start. Once it receives a start keypress, the software reads in the appropriate MIDI file, which contains a MIDI version of the target pattern, and translates the song into a set of magnet and audio commands which will be used during the presentation of the song. The software then begins a runtime loop. Each time through this loop,the software:

- checks for magnet signal, if so then writes a command to the serial connection
- checks for incoming keypress from the keyboard, if so then records key press time and note identity
- update any relevant audio or visual modules, depending on design of experiment
- update clock
- check for end of song

For the current behavioral experiment, the software was designed to display instructional information for two parts of an experimental trial. In the first part of the trial, the observation phase, the software displayed instructions for subjects to remain passive as

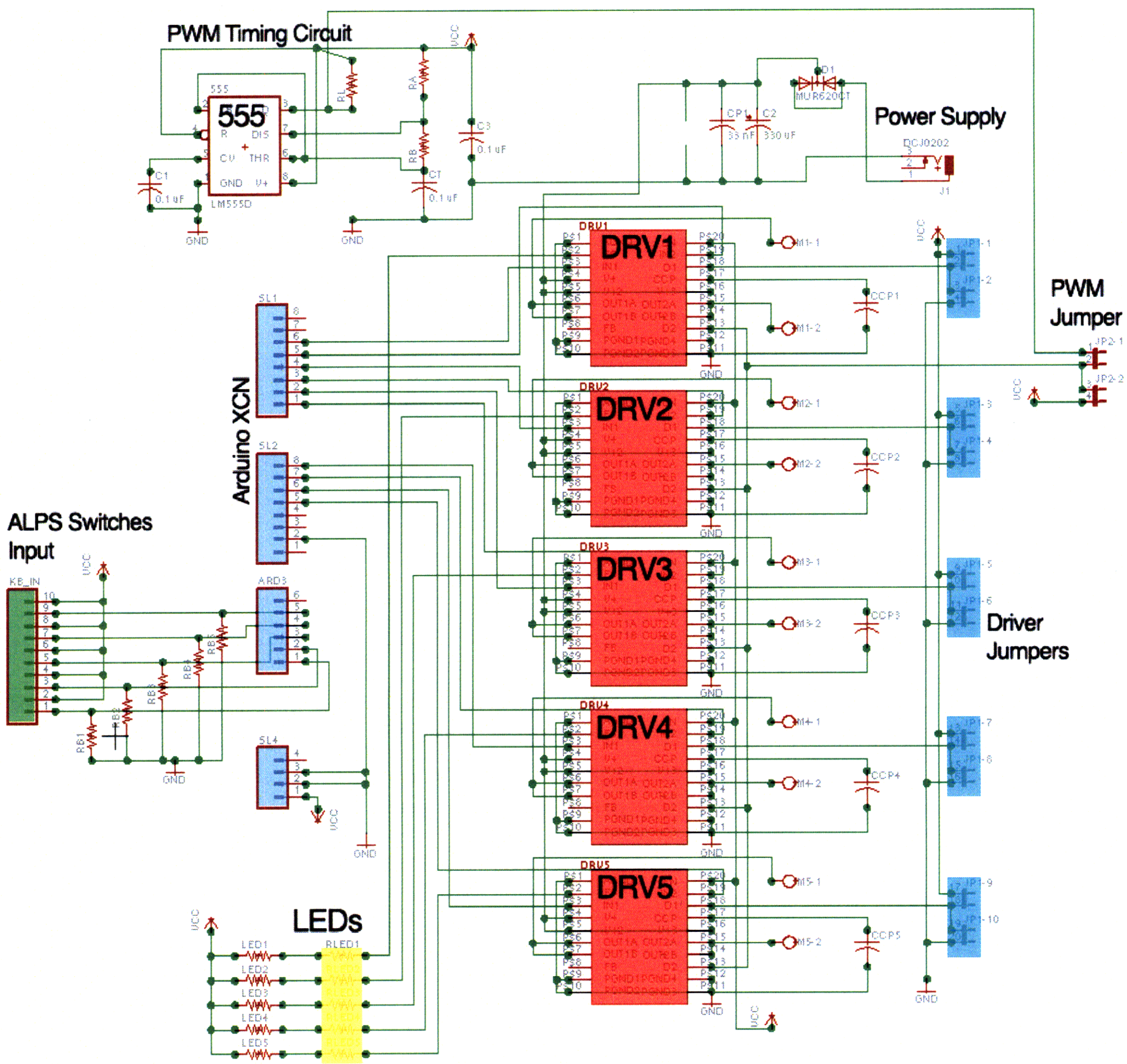

Figure 3-4: Schematic of electromagnet driver circuitry. DRV1-5 are the MC33887 H-Bridge chips. LEDs are attached to Fault Status pins on each DRV chip. A PWM Timing Circuit (2 kHz) is connected through the PWM Jumper to the Disable2 pin of each DRV chip. The PWM jumper can be switched between PWM operation and full power operation. The Power Supply is connected to each DRV chip to provide power to the electromagnets. Individual Driver Jumpers are connected to each DRV chip to selectively turn off chips. Arduino board is mounted onto set of four Arduino XCN connectors.

they observed the rhythm. In the playback phase, the software displayed instructions for subjects to playback the rhythm. Screenshots are shown in Fig. 3-6.

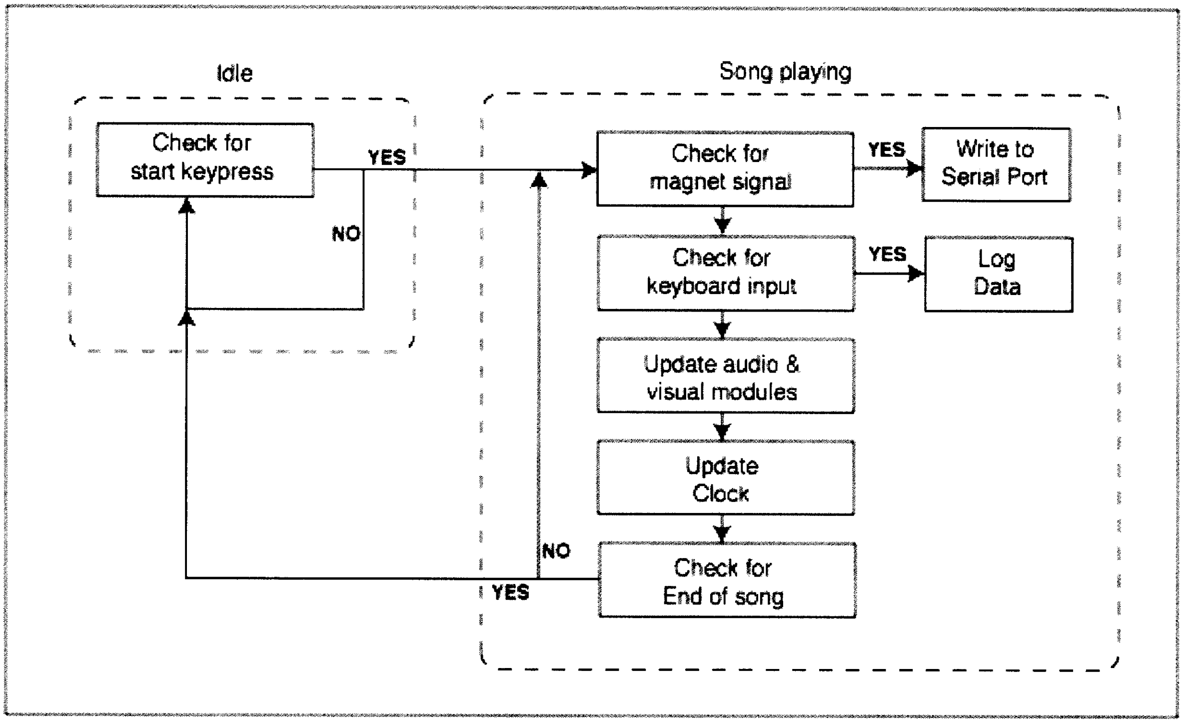

Figure 3-5: Software Flowchart. In idle mode, software awaits start keypress. Once received, a MIDI file containing the song to be learned is translated into a set of magnet and audio commands. As the song is playing, the runtime loop checks for magnet commands to send to the prototype, checks for incoming key presses, and updates audio, visual and time keeping modules.

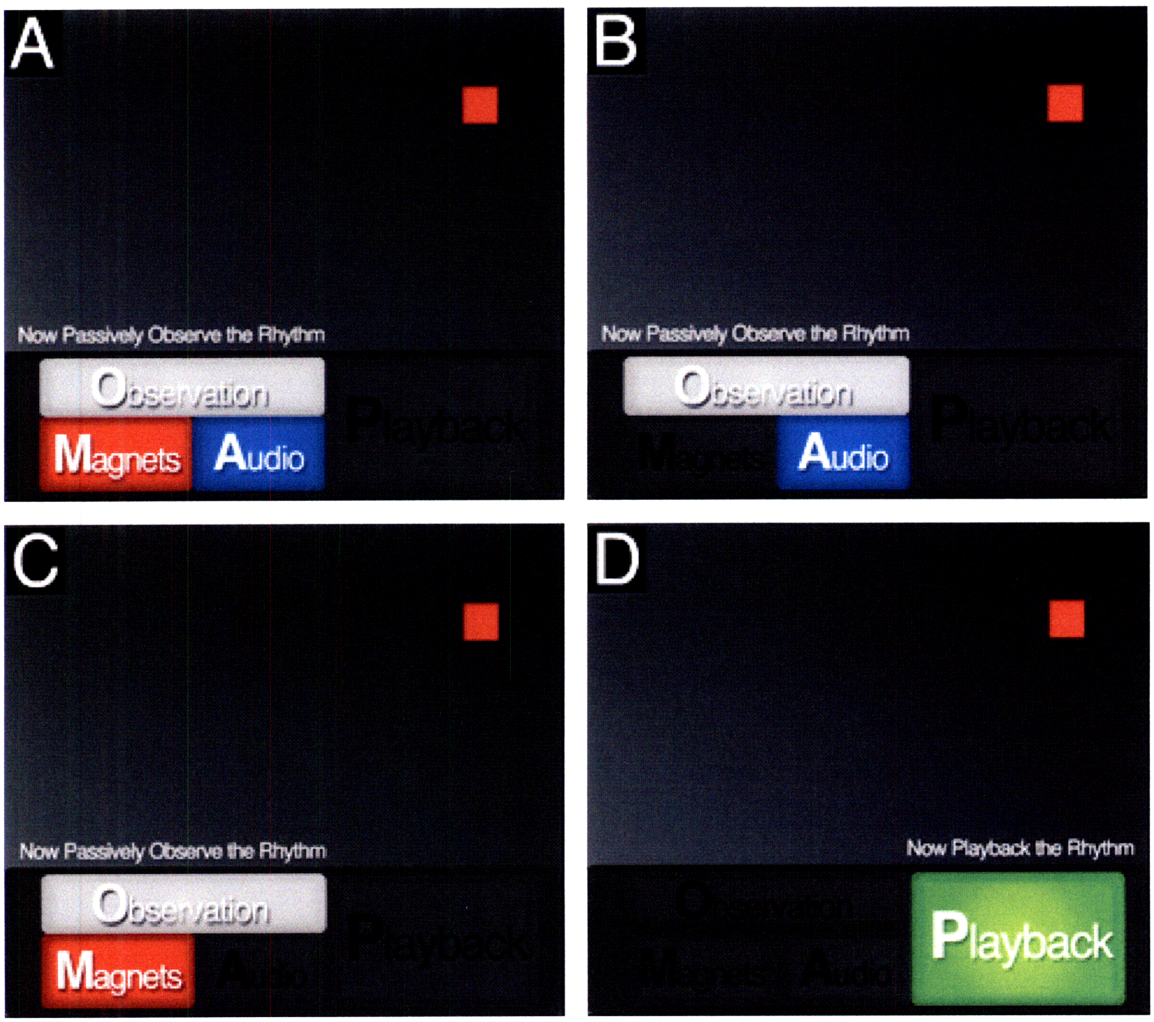

Figure 3-6: Software Screenshots. During observation mode of each trial, one of three possible instructions screens were shown (Panels A-C), corresponding to the 3 different possible experimental conditions. During playback, the subject was shown the same screen in all conditions, instructing them to play the rhythm (Panel D).

Chapter 4

Experiments

This chapter describes a set of three psychophysical experiments designed to test the efficacy of the MaGKeyS prototype keyboard. The goal of these experiments was to elucidate the manner in which haptic guidance facilitates rhythmic sequence learning. The three experiments build on each other. Experiment 1 was designed as a pilot study to coarsely validate our general approach. Experiment 2 investigated ordinal and temporal learning individually, as well as transfer effects. Experiment 3 further refined the investigation of ordinal and temporal learning, and extended the study to include a retention test conducted a day after the initial session.

4.1 Initial piloting

Several different versions of the experimental paradigm were tested before settling on the short-term memory paradigm for the following three experiments. Initially, the experiment consisted of subjects playing along with a 30-second long repetition of a 8-sec long paradiddle pattern[1]. The sequence was displayed visually on the computer screen as a moving scroll of music. This task proved to be too easy, as subjects quickly learned how to play along with the pattern after a few repetitions. Another variation of the experiment had subjects replicating shorter temporal sequences consisting of temporal intervals related by prime integers. For instance, subjects would first observe and then have to replicate a temporal sequence consisting of intervals of the following sizes: 300 ms, 500 ms, 700 ms. The thinking behind this variation was to see if non-rhythmic timing patterns could be better taught with

[1] A paradiddle is a percussive rudiment consisting of a four-note pattern of RLRR or LRLL [84]

the prototype device. Finally, the stimuli from Graham Grindlay's Master's thesis [82] were adapted for use with the keyboard. These eight-note stimuli consisted of temporal intervals of ratio size 1 (250 ms), 2 (500 ms), 3 (750 ms), and 4 (1000 ms). The four sequences used in Grindlay's study were: 2211231, 4132211, 3121142, 1122241, and were all played on a single drumstick. Therefore only temporal learning was engaged. For our adaptation, the sequences were combined with the ordinal pattern: BABABABA. The pilot testing with these stimuli proved adequate for showing a significant difference between audio-haptic and audio-only learning with an early handful of pilot subjects. However, many subjects reported that some of the sequences were easier to learn than others. Experiment 1 was developed by refining these stimuli to be of equal difficulty.

4.2 Experiment 1

4.2.1 Background & Hypothesis

The rationale for Experiment 1 is derived from previous studies of rhythmic sequence learning. Some of the earlier work used a Serial Reaction Time (SRT) paradigm, as discussed earlier. Subsequent work on rhythmic sequence learning has veered away from this experimental technique. Ullen & Bengtsson (2003) [72] used a short term memory task for investigating how subjects learn the ordinal and temporal structures of sequences[2]. In their experiment, subjects observed a visual representation of the full sequence, and then attempted to replicate it. They used a visual representation of their keyboard as the means of teaching the sequence. In another study looking at beat perception [74], subjects first observed the rhythmic sequence three times before playing it back from memory.

Very recently, Chen *et al.* [75] used a short-term memory task to investigate the neural substrates underlying performance of rhythmic sequences of varying complexity by both musicians and non-musicians. Subjects first listened to an audio version of the sequence, and then tapped in synchrony with the audio as it was played a second time. Three types of rhythms were investigated: metric simple (MS), metric complex (MC), and non-metric (NM). The three sequences consisted of eleven notes, and thus ten temporal intervals. Although Chen *et al.* report that the sequences contained the same number of temporal

[2]The reader is reminded that the ordinal property of a sequence refers to the order of elements (in this case notes) in the sequence, while the temporal property of a sequence refers to the timing intervals between successive elements in the sequence

intervals, a careful examination reveals that this is not entirely correct. The behavioral measurement methods of Chen *et al.* do not seem to indicate measurement of the length of the last note in the sequence. Chen *et al.* report that the temporal sequences are as follows: 21124113125 (MS), 21143111522 (MC), 41211523211 (NM) [3]. However, if the length of the last note is not measured, there is no certainty that the length of the last note in each sequence is performed by the subject; the subject could easily disregard holding down the last note for its full duration and it would not affect the measurement. In other words, when using temporal sequences that end if different note lengths, as in Chen *et al.*, we must be careful in ensuring whether or not subjects actually execute the length of the last temporal interval. It could easily be argued that the sequences that subjects effectively learned in Chen *et al.* did not contain the last temporal interval, and therefore would be: 2112411312 (MS), 2114311152 (MC), 4121142321 (NM). When viewed from this perspective, we see that the sequences effectively do not contain identical temporal interval sizes, because the last temporal interval is not followed by another keypress which ensures the execution of the full length of that temporal interval. In the current experiment, this issue is controlled by using sequences in which the length of the last keypress is identical (250 ms). This ensures that identical temporal intervals are realized in each sequence.

In the current experiment, an auditory-motor short term memory task was used to test how haptic guidance facilitates the learning of a new rhythmic sequence. Subjects observed the target sequence in one of three conditions: audio and haptic (AH), only audio (A), or haptic only (H). Subjects were instructed to replicate the rhythmic sequence after each observation, and key press data of their performance was used to analyze how well the sequence was learned. The target rhythmic sequences were similar to the metric complex rhythms of Chen *et al.* [75], and were adapted from Essens & Povel[66] to have a moderately complex rhythmic structure (see Methods for complete description of sequences).

Our hypothesis tested in this Experiment 1 is as follows:

- $\boldsymbol{H}_0$: *Haptic guidance, used in conjunction with audio, facilitates learning of rhythmic sequences, resulting in better performance (less error) when compared with audio-only learning.*

Drawing on the background of motor skill acquisition literature covered earlier, why

[3]Corresponding interval lengths: 1= 250 ms, 2 = 500 ms, 3 = 750 ms, 4 = 1000 ms, 5 = 1500 ms.

would we expect differences between conditions in this experiment? According to the ecological approach to motor learning, we can think of our experimental task as a perceptual-motor space in which the subject will have to "search" for the right solution in order replicate the sequence. Each experimental condition involves presenting information to the user in a unique form. Therefore, performance in each condition should reflect the operational capabilities of audio and haptic modalities in facilitating short-term recall of a motor sequence. In this respect, we would expect the condition in which the most information is presented, the audio + haptic condition, to result in the best performance, while the other conditions should reflect the individual capabilities of each perceptual channel at facilitating task performance.

4.2.2 Methods

Subjects

Twelve subjects participated in this experiment, ranging in age from 18 to 52 years old, with a mean of 28 years of age. All subjects were right-handed, and reported having little to no formal piano training. Subjects participated in the experiment by completing a 60 minute long session in our lab, and were compensated financially for their participation. The experimental protocol was approved by the MIT Committee On the Use of Humans and Experimental Subjects, under COUHES protocol #0708002363. Informed consent was obtained from all subjects prior to beginning the experiment.

Behavioral paradigm

Procedure Figure 4-1 shows a schematic of the experimental setup. Each session comprised three blocks of learning. In each block, a different target sequence and experimental condition was tested over 30 trials. Each trial comprised two parts: observation and playback. During observation, subjects were instructed to passively observe the target sequence.

Each trial began with a 4-beat audiovisual countdown, followed by the observation phase. After observation, another 4-beat audiovisual countdown was played, after which the subject was instructed to play back the target sequence. The length of the playback period was extended two seconds beyond the length of the observation period to ensure that slower renditions of the target sequence would not be cut off. We had observed through

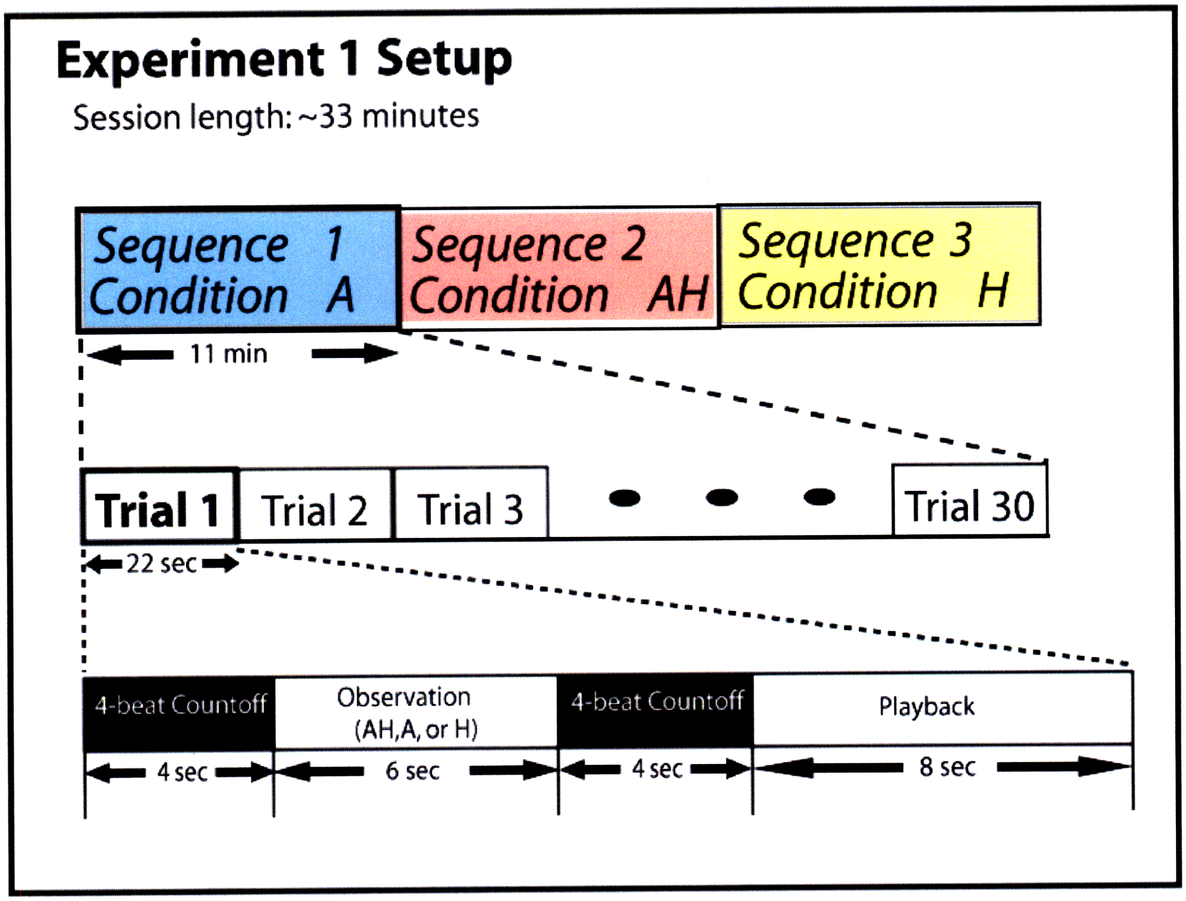

Figure 4-1: Experiment 1 Behavioral Paradigm. Subjects completed 3 blocks of training, each consisting of 30 trials, in which they learned to perform a different rhythmic sequence under a different experimental condition. Refer to text for description of experimental conditions, and to 4-2 for a description of the target sequences.

prior piloting on this experimental setup that subjects often take longer to play back a sequence when learning it; therefore, we extended the playback period accordingly.

Experimental conditions Three different experimental conditions were tested for the observation phase of the trial:

1. **AH**: Target sequence is presented using both audio and haptic perceptual channels. In this mode, the subject feels their fingers being pulled into the keypress via the magnetic action of the keyboard, while hearing audio tones corresponding to the keypresses.

2. **A**: Target sequence is presented using only audio. In this mode, subjects just listen to audio tones corresponding to the target sequence.

3. **H**: Target sequence is presented using only haptic guidance, with no corresponding audio. In this mode, subjects just feel the target sequence, without hearing it.

All subjects were explicitly instructed to remain passive during all observation phases. This was done to ensure that subjects refrained from slight movements during condition A, in which subjects just listened to the target sequence. If subjects were to move in time with the audio stimulus during observation on condition A, this could well qualify for physical practice, and could confound the data. Therefore, subjects were instructed to refrain from any type of correlated motor movements, such as slightly moving the fingers of the right or left hand, or tapping their foot or nodding their head to the rhythm.

The 3 sequences and 3 conditions composed 9 possible sequence/condition pairs. With 12 subjects completing 3 blocks each, this arrangement provided for 36 sequence/condition pairs in total. For proper control, sequence/condition pairs were balanced across the subject pool such that each of the 9 possible sequence/condition pairs was tested 4 times, and the 4 instances of each pair were balanced across the first, second, and third presentation blocks. While this approach is not completely exhaustive, it mixes up the presentation of sequences and conditions enough so that we do not believe there is any learning effect present in the results.

Stimuli Figure 4-2 shows the three sequences tested in our experiment. Sequences were adapted from [66] and designed to be of equal complexity while remaining significantly different from one another. Each sequence consisted of 10 notes, with 9 subsequent timing intervals. The ordinal property of each pattern, which is the order of the notes, was kept the same across all sequences: BABABABABA. The timing pattern, however, varied across all the sequences. Each sequence contained the same number of timing interval durations, arranged in a different order. At 60 bpm, the tempo at which all sequences were presented to the subject, the timing interval sizes are as follows: 1 = 250 ms; 2 = 500 ms; 3 = 750 ms; 4 = 1000 ms. Each sequence contained five 1 intervals, two 2 intervals, one 3 interval and one 4 interval, such that each sequence was composed from the following set of temporal intervals: 111112234.

The order of the temporal intervals was derived from the stimuli used by Povel & Essens [66]. In their seminal work on gauging the "rhythmicity" of different stimuli, Povel & Essens generated different categories of rhythms from the same base set of possible temporal intervals. Depending on the organization of the termporal intervals, some categories of stimuli resulted in a stronger internal clock, indicating that they were rhythmically "more simple" and therefore easier to play. Povel & Essens postulated that the strength of this internal clock was proportional to the amount of temporal regularity in a sequence. For instance, a rhythmic sequence such as 211211 will induce a much stronger internal clock that a sequence such as 231321. This is because the 211211 sequence induces a much stronger sense of regularity at the temporal interval size of 1, while the 231321 interval does not induce a strong sense of temporal regularity. This sense of temporal regularity is more colloquially referred as "feeling the beat." Povel & Essens created a computer program to quantify the strength of this internal clock. Using the following base set of temporal intervals, 11112334, they described nine different categories of rhythmic sequences, with Category 1 being the most rhythmically simple arrangements, and Category 9 is the most rhythmically complex arrangements.

Here, we adapted rhythms from Category 3 of the Povel & Essens stimulus set. In this category, the temporal intervals are grouped such that the downbeat, or every 1000 ms, is always accented by a note. However, the half down beat, or every 500 ms, is not necessarily accented every time. It was thought that choosing a set of temporal intervals in this mid-range of complexity would provide for a stimulus set of sufficient difficulty for subjects to have some difficulty learning.

All MIDI replications of the sequences were generated using Reason, an audio synthesis software (Propellerhead Software, Sweden). All audio was presented over Sony MDR-7650 headphones at an audibly comfortable level. During observation conditions involving audio presentation, piano tone notes were cued by the software program to sound at the appropriate times. Therefore, in the AH stimulus condition, the sounded audio was not generated from the keypresses enacted by the magnetic keyboard, but were instead "artificially" generated by the software. This was done to ensure that, in the event the subject resisted a keypress during magnetic control or in the event that the haptic feedback did not work entirely correctly, the subject would still be hearing a valid version of the audio. The timing of the magnetic keypress actuation and sounded audio was calibrated to be accurate within 5 ms. In the playback condition, audio tones were triggered by the actual keypresses of the subject. The tones used for the keypresses and audio presentation were generated from Reason grand piano tones, with the corresponding frequencies for the index and middle finger keys: D = 293 Hz and E = 329 Hz.

Setup

Subjects were seated in a chair in front of a table with a monitor and the keyboard. Subjects were instructed to place their right hand on the keyboard device until they felt completely comfortable pressing down the two buttons with their index and middle fingers. Since each subject's hand is different, it was important to ensure that each subject was equally comfortable with the placement of their hand on the keyboard. Subjects were instructed to adjust the height of the chair, the orientation of the keyboard and the orientation of the chair, until they felt completely comfortable. They were instructed to continue adjusting until they could completely relax their forearm and elbow on the armrest of the chair. In some cases, this involved placing a 3" foam pad on top of the armrest underneath the subject's forearm, in order to ensure that they were not straining their arm muscles.

Once the subject was comfortably situated, permanent magnets were attached to the fingertips of their index and middle fingers using paper tape. The use of paper tape was chosen over a prior method, a glove with magnets in the fingertips, because I realized that every person's hand is different, and each person interfaces to the keyboard in a different way. Therefore, it was necessary to place the magnets in a position that felt natural to the subject, and allowed them to execute keypresses in a manner that felt comfortable.

The method for attaching the magnets to the fingertips is as follows. Once the subjects was situated comfortably in the chair and could comfortably press down both keys, a magnet (with paper tape attached) was placed underneath the pad of their index finger. The subject was instructed to alternatively press down both keys, with the magnet under the index finger, and once they were completely comfortable with how their finger rested on the magnet, the magnet was then taped to the finger. The subject was then instructed to continue pressing down the key and to report whether or not the taping of the magnet felt comfortable and did not impede their ability to press down the key. In some cases, the magnet had to be readjusted. Once the index finger magnet was successfully attached to the index finger, the same procedure was repeated for the middle finger magnet.

Each trial started with a four beat visual and auditory countdown synchronized with to a 60 bpm metronome. All observation conditions lasted only 4 beats (4 sec at 60 bpm). On the fifth beat after the beginning of the observation trial, the playback trial began. Each playback trial was longer, however, for a length of 6 beats. This expansion in the playback interval was a result of the early observation in preliminary pilot experiments that subjects, while learning these new sequences, would often lag in tempo behind the metronome, but still play the correct sequence.

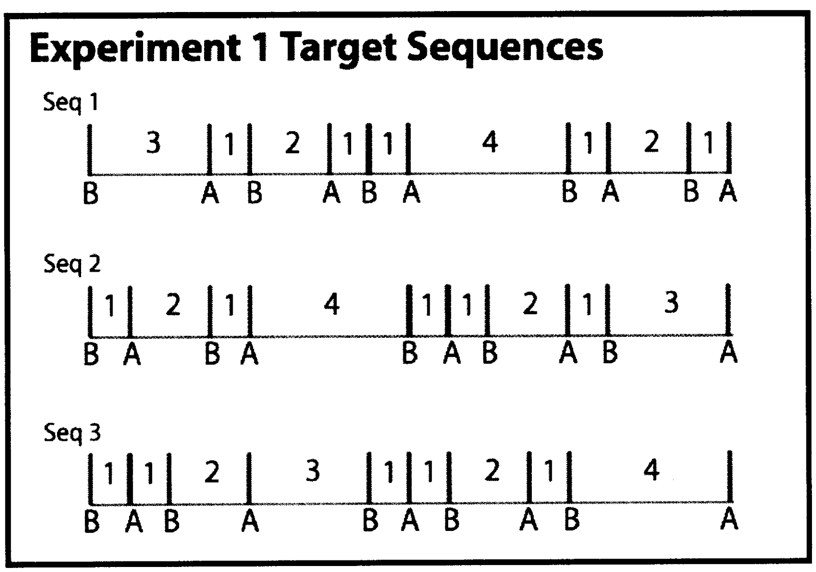

Figure 4-2: Target rhythmic sequences for pilot experiment. All sequences were presented at 60 bpm, such that 1 = 250 ms, 2 = 500 ms, 3 = 750 ms, 4 = 1000 ms. Note A corresponded to a piano note of D4 = 293 Hz, and B corresponded to E4 = 329 Hz. All three sequences consisted of the same ordinal sequence, but different temporal sequence.

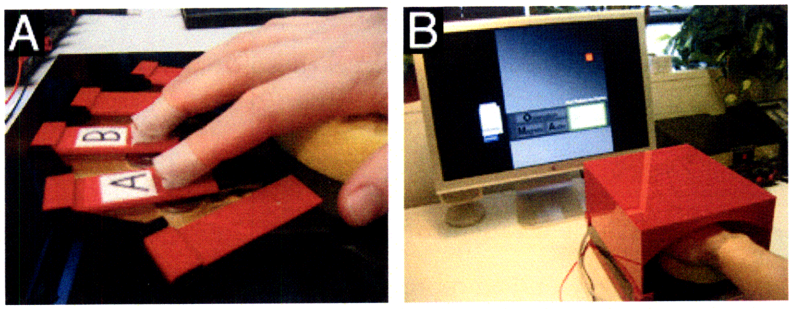

Figure 4-3: (Left) Sideview photograph of prototype with typical configuration of user's hand during experiment. Paper tape was used to attach permanent magnets to the finger tips. (Right) Photograph of experimental setup. An acrylic shield is placed over keyboard to prevent subjects from using visual cues, such as watching their fingers being pulled down by the keyboard, during the experiment.

Data Analysis

Onset times and note identity were recorded for each playback session from each trial. The onset times and note identity were compared with the target sequence using a variant of the Dynamic Time Warping algorithm. On our first pass analysis, we only analyzed the data for how correctly the ordinal sequence was replicated. That is, we only considered the order of the notes played, without taking into account the relative timing of the note presses. This was done because it was realized that the difficulty of the sequences was such that many subjects never achieved full proficiency at playing the sequences, even after 30 trials. Therefore, it is difficult to compare the accuracy of timing in a playback session where the ordinal sequence is not captured correctly. We therefore decided to only consider ordinal errors as the criterion for the correctness of the playback.

4.2.3 Results

Figure 4-4 shows performance in each condition and trial averaged across subjects. A two-way ANOVA, with condition and trial as the factors, revealed strong effects for both condition, $F(2,58) = 34.27$, $p << 0.0001$, and for trial number, $F(29,58) = 3.65$, $p < 0.0001$. It makes sense that there would be an effect of trial, since each block of thirty trials involves subjects learning to perform a new sequence. Therefore, one would expect performance to improve naturally over the course of thirty trials.

This effect is highlighted when we perform separate analyses on the first half (1-15) and second half (16-30) of trials. A two-way ANOVA on trials 1-15 reveals strong effect of condition, $F(2,28) = 18.71$, $p << 0.0001$, and trial, $F(14,28) = 3.30$, $p < 0.01$. However, a two-way ANOVA on trials 16-30 only reveals an effect for condition, $F(2,28) = 38.33$, $p << 0.0001$, but not trial, $F(14,28) = 1.03$, $p = 0.46$. This strong effect for condition in trials 16-30 is quite remarkable. Since no effect for trial was found, I averaged across trials 16-30 to generate the bar graph in Fig. 4-5. Visual inspection of this bar graph indicates that the haptic guidance, when accompanying audio information, significantly facilitates performing of the rhythmic sequences. A one-way ANOVA (with condition as the factor) for the last half of trials (16-30) of conditions A and AH revealed a very strong effect of condition, $F(1,28) = 94.67$, $p << 0.0001$. When this same analysis was performed for the last half of trials (16-30) of conditions A and H, a similarly strong effect of condition was also demonstrated: $F(1,28) = 20.10$, $p < 0.001$.

This last result is an important point. We observed drastic differences between conditions: when subjects were given both haptic and audio information (AH), they performed significantly better than when provided with just audio (A). This result was observed despite the fact that subjects had enough difficulty with the stimulus set so they could not adequately perform the sequence by the end of the learning block.

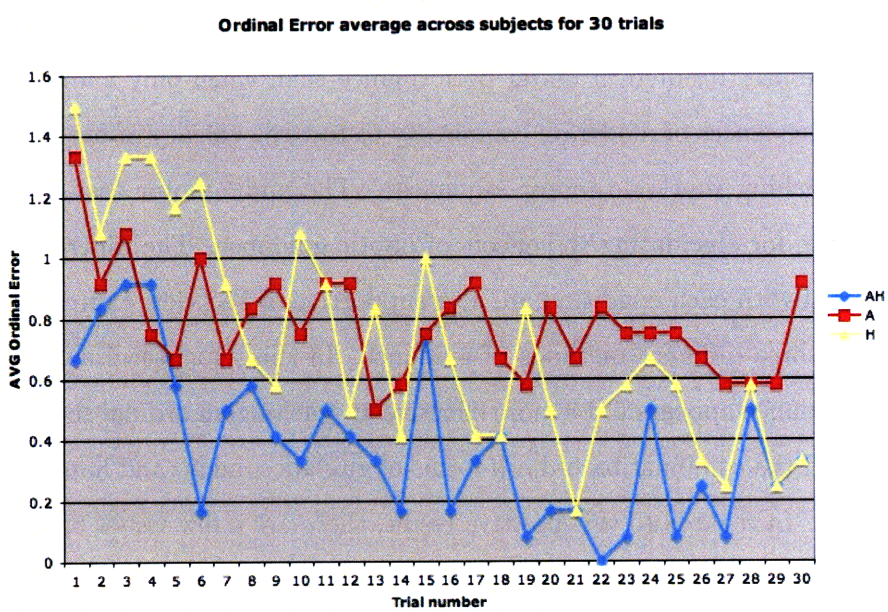

Figure 4-4: Experiment 1 Results. Ordinal error is averaged across subject (N = 12) and plotted by trial for each condition.

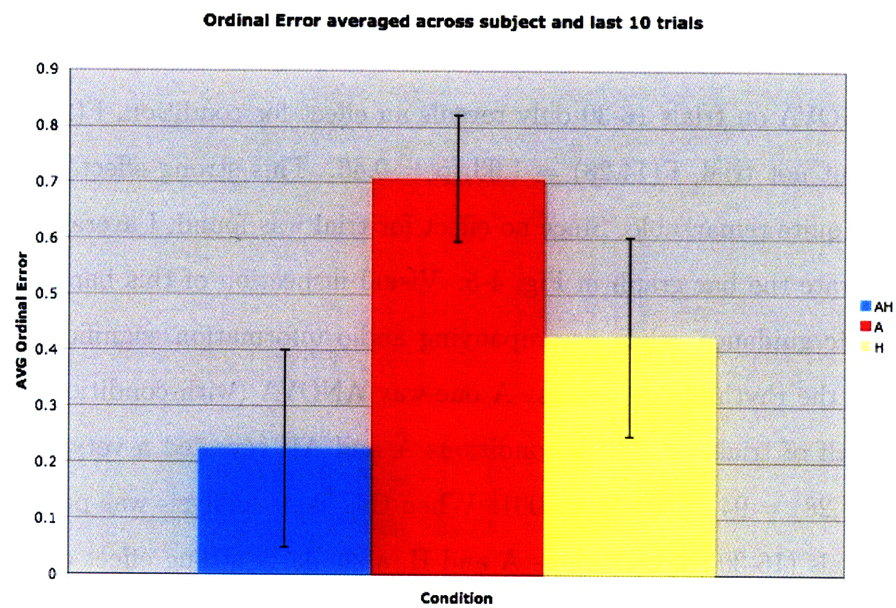

Figure 4-5: Experiment 1 Results. Average of trials 16-30 from Fig 4-4. Error bars are standard deviation.

4.2.4 Discussion

The results presented here are consistent with the hypothesis presented at the beginning of this section. In our experiment, the condition where both audio and haptic information was presented to the user resulted in better performance than when only audio was used. We used rhythmic sequences of moderate complexity to test the efficacy of our electromagnetic keyboard in teaching rhythmic motor sequences. The audio-motor task seems to be an effective medium for elucidating the effects of haptic guidance. The different performance levels associated with each condition are also supportive of the view expressed earlier that we are testing three different methods of guidance. In this short-term audio-motor recall task, haptic guidance appears to be more effective at teaching an ordinal sequence than just audio alone, and the combination of both forms of guidance, audio and haptic, provides the greatest benefit. In regards to this positive result, there are a few issues to be considered:

Stimulus complexity / task difficulty As discussed in the data analysis section, subject performance was such that many of the subjects were still making ordinal errors during the end of each block. Therefore, we were only able to compare ordinal data across subject and condition, but not temporal data. Since the end of each target sequence consisted of a different combination of temporal intervals, it became difficult to measure temporal performance when two or more ordinal errors were present. We suspect that this was due to the complexity of the stimuli. For our subject population, musically-naive subjects, playing a sequence of 10 notes of different temporal interval sizes is moderately to sufficiently difficult. Our goal for the next experiment was to modify the complexity of the stimuli such that the ordinal properties of the sequence can be learned adequately during the experimental session.

Behavioral experiment design Our first stimulus selection challenged the user with learning both the temporal and ordinal properties of a sequence simultaneously. As mentioned earlier, prior studies into rhythmic learning have produced evidence indicating that different areas of the brain mediate learning of these two types of information. Therefore, subsequent experiments aimed to distinguish how haptic guidance facilitates learning of these two qualities of a rhythmic sequence.

Transfer & Retention Two more issues to be considered are transfer and retention of motor learning, which were not tested in the current behavioral paradigm. Motor learning transfer could be demonstrated by first training subjects on a particular set of stimuli, and then later testing on a new set of untrained stimuli to see if any demonstrable improvement is observed. Motor learning retention could be demonstrated by testing subjects' ability to play the target rhythms at a later time, either at the end of the experiment or the day after. Experiments 2 & 3 aimed to address both the issues of motor learning transfer and retention.

4.3 Experiment 2

4.3.1 Background

Experiment 1 tested subjects' ability to replicate a 10-note rhythmic musical sequence that varied in both ordinal and temporal domains, under three learning conditions: AH, A, and H. As discussed previously, recent neuroscience studies have revealed that different mechanisms underlie learning the temporal and ordinal properties of a sequence [71, 72]. In Experiment 1, temporal and ordinal learning mechanisms were engaged simultaneously during all learning. In Experiment 2, our goal was to understand how haptic guidance independently modulates ordinal and temporal learning. To accomplish this, the behavioral paradigm of Experiment 1 was shortened and replicated.

In Experiment 2 (Fig. 4-6), subjects first executed a 3-stimulus block, under conditions AH, A and H, in which the stimuli were 6-note sequences that only varied in the ordinal domain. In this block of testing, which will be referred to as Experiment 2, Ordinal Block, subjects engaged in ordinal sequence learning under the 3 experimental conditions. If haptic guidance facilitates ordinal learning, then we would expect to see smaller error measurements for conditions AH & H, than for condition A in Experiment 2, Ordinal Block.

In the second block of testing, which will be referred to as Experiment 2 Temporal Block, subjects engaged in temporal sequence learning by testing three 6-note sequences that only varied in time, again under conditions AH, A and H. If haptic guidance facilitates temporal learning, then we should observe smaller temporal error measurements for conditions AH & H, than for condition A in Experiment 2 Temporal Block. However, if haptic guidance does not facilitate temporal learning, at least any more than audio, then we might expect to see higher amounts of error for condition H, the condition in which audio is absent.

A final block of testing, Experiment 2, Combined Block, was created to test how the advantageous effects of haptic guidance, like those seen during the Ordinal block, transfers to a condition in which the subject is learning a new rhythmic sequence. Subjects learned three new sequences that varied in both ordinal and temporal domains. However, in order to test transfer,the sequences in the Combined block were all presented using just audio, identical to condition A in Experiment 2 Ordinal Block and Experiment 1. The ordinal and temporal properties of each sequence in the Combined block were formed by pairing sequences that were run separately under the same condition in the prior Ordinal and Temporal blocks.

Each subject tested one combined stimulus in which the ordinal and temporal components were each learned under condition AH in the prior two blocks (condition AH/AH), another combined stimulus in which the ordinal and temporal components were each learned under condition A in the prior two blocks (condition A/A), and another combined stimulus in which the ordinal and temporal components were each learned under condition H in the prior two blocks (condition H/H). By conducting each sequence of the transfer test under condition A, a scenario is created in which we would expect performance differences between the sequences *only* if there was a transfer effect. If there is a transfer effect for the haptic guidance advantage, then we might expect to see lower error measurements for condition AH/AH in Experiment 2 Combined Block. However, if there is no transfer of the haptic guidance advantage seen in either Ordinal or Temporal blocks, then we would expect to see no difference between the three conditions in the Combined Block.

4.3.2 Methods

Subjects

Thirteen new subjects participated in this experiment, ranging in age from 19 to 47 years old, with a mean of 28.6 years of age. All subjects were right-handed, and reported having little to no formal piano training. Subjects participated in the experiment by completing a one hour long session in our lab, and were compensated financially for their participation. The experimental protocol was approved by the MIT Committee On the Use of Humans and Experimental Subjects, under COUHES protocol #0708002363. Informed consent was obtained from all subjects prior to beginning the experiment.

Behavioral paradigm

Figure 4-6 shows a schematic of the behavioral paradigm used in Experiment 2. Within a trial, the behavioral paradigm did not differ from Experiment 1, in that subjects still were completing an auditory-motor short-term memory task. The overarching structure of the experiment, however, changed substantially from Experiment 1. Each session comprised 3 experimental blocks of learning: Ordinal, Temporal, and Combined. Within each of those blocks, three sequences were tested, each under a different experimental condition.

Experiment 2 Ordinal Block In Experiment 2 Ordinal Block, subjects executed the first three sequences found in Fig. 4-7. These stimuli only vary in the ordinal domain, and therefore engage the subject primarily in ordinal learning. The sequences comprise 6 notes of equal duration, 500 ms, and vary between 3 possible note values: note A corresponds to the index finger and a tone of 293 Hz (D4), note B to the middle finger and a tone of 329 Hz (E4), and C to the ring finger and tone of 370 Hz (F#4). The conditions tested were AH, A and H (refer to Exp. 1 for description of conditions).

Experiment 2 Temporal Block In Experiment 2 Temporal Block, subjects executed the first three sequences found in Fig. 4-8. These sequences only vary in the ordinal domain, and therefore primarily engage the subject in temporal learning. The sequences comprise 6 notes, all note A (the index finger), which varies in time. The temporal intervals used were 1 = 250 ms, 2 = 500 ms, and 3 = 750 ms. Each target sequence consisted of 3 250 ms intervals, 1 500 ms interval, and 1 750 ms interval, such that each sequence was composed from the following set of temporal intervals: 11123. The intervals were designed to be of moderate complexity, but still learnable within a single session. Each of the three sequences in the Temporal block were also paired by experimental condition, such that subjects learned one of the three temporal sequences under AH, another sequence under A, and another under H. The sequence/condition pairings & presentation orders (first, second, third) were controlled such that each possible pairing of sequence/condition/order was tested the same number of times.

Experiment 2 Combined Block In Experiment 2 Combined Block, subjects executed three sequences from the set of sequences found in Fig. 4-9. These sequences vary in both ordinal and temporal domains. Only the combined sequences consisting of Ord1, Ord2, Ord3, Temp1, Temp2, and Temp3 were used in Experiment 2 Combined block[4]. This meant that there were nine sequences from which to choose three for each subject. The three sequences tested by each subject were determined by the sequence/condition pairings in the prior Ordinal and Temporal blocks executed by that subject. The three combined sequences are formed by combining the ordinal and temporal sequences which are tested under the same condition. For instance, if a subject tests sequence Ord2 under condition AH

[4]The nine sequences used in Experiment 2 Combined Block were: Ord1Temp1, Ord1Temp2, Ord1Temp3, Ord2Temp1, Ord2Temp2, Ord2Temp3, Ord3Temp1, Ord3Temp2, and Ord3Temp3.

in the Ordinal block, and then tests sequence Temp1 under condition AH in the Temporal block, Ord2Temp1 would be one of the three sequences which the subject tests in the Combined block. The other two combined sequences would be formed by combining the ordinal and temporal sequences learned under condition A and H, respectively. We will refer to the conditions of each of these sequences as AH/AH, A/A, and H/H, respectively.

1. **AH/AH**: Target sequence consists of an ordinal and temporal pattern that were each trained under condition AH in the prior Ordinal and Temporal blocks. Target sequence presented using only audio.

2. **A/A**: Target sequence consists of an ordinal and temporal pattern that were each trained under condition A in the prior Ordinal and Temporal blocks. Target sequence presented using only audio.

3. **H/H**: Target sequence consists of an ordinal and temporal pattern that were each trained under condition H in the prior Ordinal and Temporal blocks. Target sequence presented using only audio.

In Experiment 2 Combined block, all three sequences were tested under the same condition A. This was done to allow for testing of the effects of transfer. Testing the three sequences under the same condition means that a performance difference should only arise if there is an intrinsic advantage in one or more of the stimuli. In other words, if there is no effect of transfer from the prior blocks, then we would not expect to see any difference in performance for the three sequences of the Combined block. However, if a transfer effect exists, then we expect to see less error (better performance) for conditions AH/AH and/or H/H than for condition A/A. However, if no transfer effect exists, then we would expect to see equivalent performance for the three conditions.

Data Analysis

Subject performance was analyzed in terms of ordinal and temporal error. To quantify ordinal error, a method similar to Experiment 1 was used. A dynamic programming matrix was used to create a best fit between a subject's ordinal response and the target ordinal sequence for each trial response. The output of this process is the number of ordinal errors in a subject's response during a particular trial. The greatest number of ordinal errors a

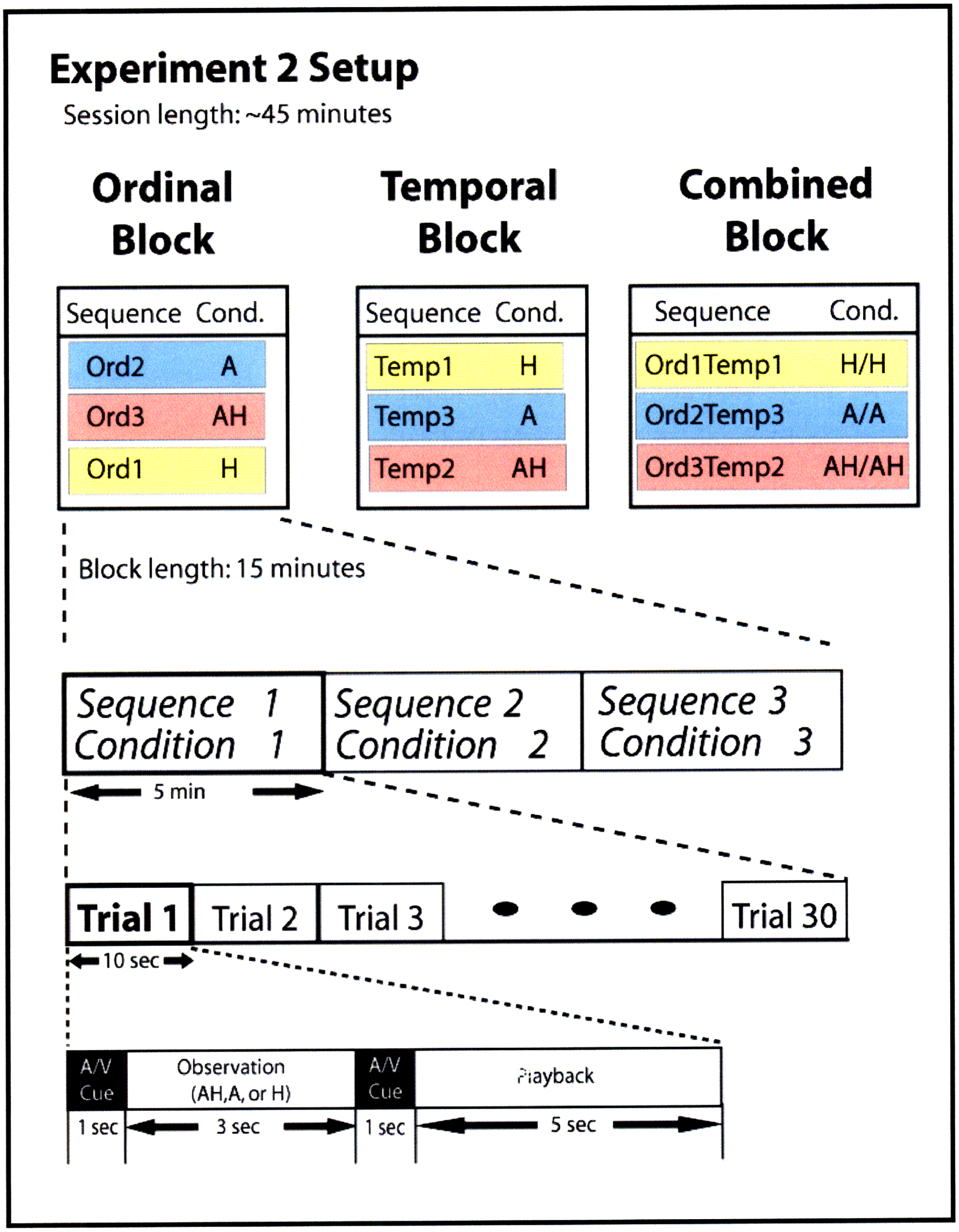

Figure 4-6: Experiment 2 behavioral paradigm. Subjects tested three blocks of learning: Ordinal, Temporal and Combined. In each block, a different sequence was tested under a different condition. Refer to text for description of conditions, and to Figs. 4-7,4-8, and 4-9 for descriptions of target sequences.

subject could have in one trial is the same as the number of notes: 6 (any extra notes beyond six are not counted). Ordinal error was averaged across subjects for each trial and condition to generate the graphs in Fig. 4-10A, 4-11A, and 4-12A. Additionally, the last 15 trials were averaged to generate bar graphs (Figs. 4-10B and 4-12A).

Temporal error was quantified by measuring the time between successive keypresses to generate a list of interval values for each trial playback. For the 6 note sequence, there are 5 temporal intervals. The raw temporal interval measurements are averaged across subject for each trial and condition to generate the line graphs in Fig. 4-10C, 4-11B, and 4-12B, which show profiles of the temporal intervals across the 30 trials of learning. For the Temporal and Combined blocks, temporal data was further process in two ways: absolute and ratio timing.

When considering how to quantify timing error in a rhythmic performance, we can think of analyzing the error in two ways. The first way, which we call absolute time, involves measuring error in terms of the absolute difference in time between the performed interval and the target interval. For instance, consider a five-note pattern consisting of the following four temporal intervals: 500ms - 250ms - 750ms - 250ms. If a subject performed this rhythm and we measured temporal intervals of the following values: 600ms - 300ms - 650ms - 300ms, then we could calculate the absolute temporal error by taking the absolute value of the difference between intervals. This would result in an error measurement of: (600-500) + 2*(300-250) + (750-650) = 300 ms. Temporal data is processed with respect absolute timing and displayed in the graphs of Fig. 4-11C-E and 4-12C-D. Figs.4-11C and 4-12C show X-Y plots of the interval size for each condition for the last 15 trials. The diagonal black line represents "target" performance. The absolute amount of deviation from this line is calculated as the absolute timing error, and is averaged across subject for each trial and condition and plotted in Figs. 4-11D and 4-12D. The average of the last 15 trials of absolute timing error is shown in Figs.4-11E and 4-12D.

Another way to quantify temporal error in a rhythmic sequence is by considering the ratio of interval sizes. Often when learning to perform a rhythmic sequence, subjects will execute the rhythm at a slower tempo, meaning that the absolute timing of the intervals lengthen, but the ratio of interval sizes stays constant. In a situation where a rhythmic sequence is executed at a slower tempo, analyzing temporal error in terms of absolute time does not tell the whole story. We can calculate the ratio temporal error by taking the value of the larger intervals and dividing them by the average of the smaller interval sizes, and then taking the difference between this number and the correct interval ratio size. Considering our previous example, then, the calculated ratio temporal error would be: abs[(600 / 300) - 2.0] + abs[(650/300) - 3.0)] = 0.83. Temporal error is processed with respect to ratio timing and used to generate the graphs of Fig. 4-11F-H and 4-12E-F. Figs.4-11F and 4-12E show X-Y plots of the ratio sizes for each condition for the last 15 trials. Notice that since ratio timing involves dividing the large intervals by the average size of the smaller interval, the timing error due to the smaller interval is essentially ignored. Therefore, the smallest interval is always a perfect 1.0 (as in Figs.4-11F and 4-12E) when analyzing using ratio timing. As with the X-Y absolute timing plots, the black line in the X-Y ratio timing plot represents perfect performance. The amount of deviation from this line is calculated as the ratio timing error, and is averaged across subject for each trial and condition and plotted in Figs. 4-11G-H and 4-12F. Bar graphs of the last 15 trials are also plotted.

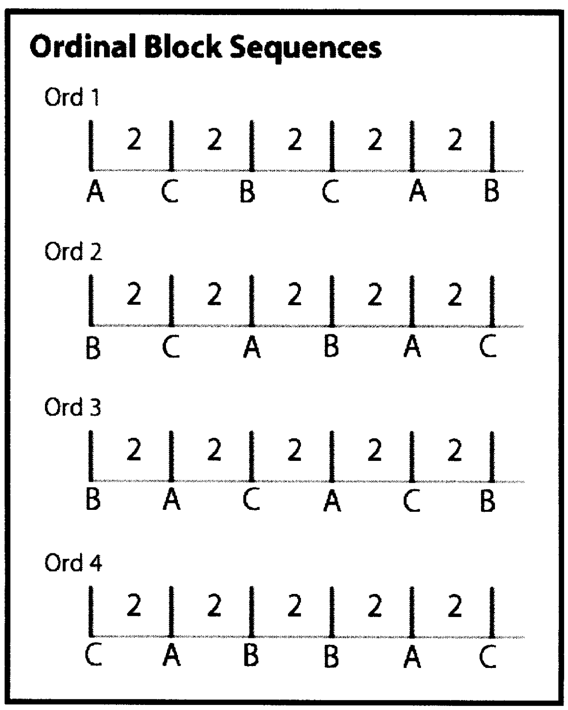

Figure 4-7: Target sequences used for Ordinal blocks of Experiments 2 and 3. Target sequences comprised 6 notes of equal temporal spacing, 500 ms. Ordinal property of each sequence was composed by combining two triad variations of the three notes (ACB,CAB,BCA,BAC) to form a six note sequence. Experiment 2 only used Ord1, Ord2, and Ord3, while Experiment 4 used all four sequences.

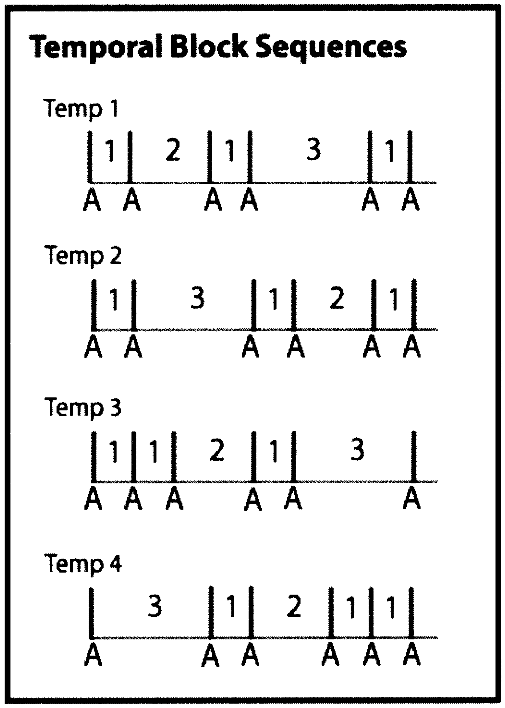

Figure 4-8: Target sequences used for Temporal blocks of Experiments 2 and 3. Target sequences comprised 6 notes, all note A, with 5 temporal intervals of varying size. Each of the four target sequences was composed from the following interval set: 11123. As in Experiment 1, these temporal sequences were designed after [66] to be of moderate rhythmic complexity. The temporal property of each sequence was composed by combining two 1000 ms-long segments of temporal intervals (121,112,211,31,13) to form the six note sequence. Experiment 2 only used Templ, Temp2, and Temp3, while Experiment 4 used all four sequences.

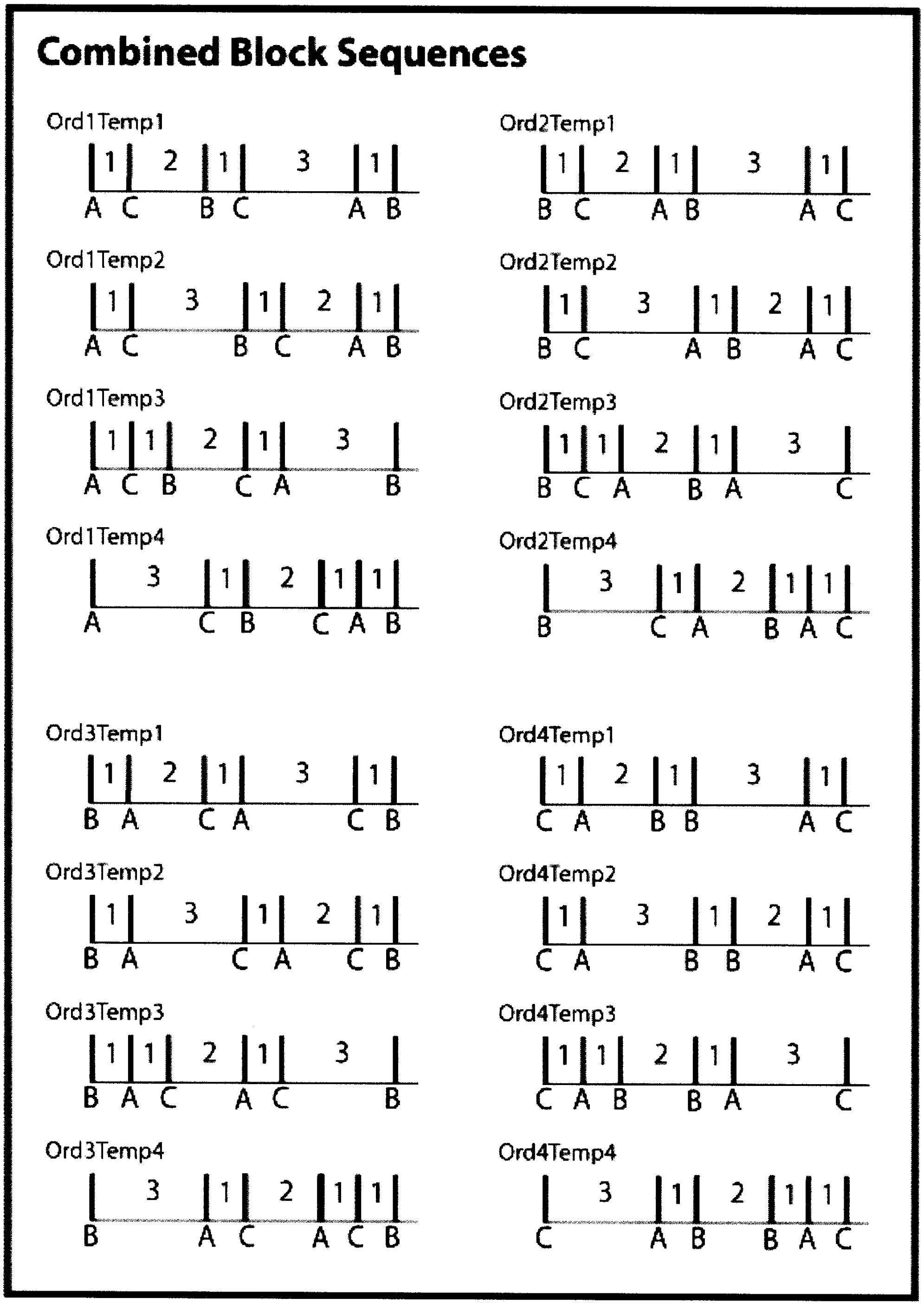

Figure 4-9: Target sequences used for Combined blocks of Experiments 2 and 3, and Experiment 3 Retention block. All sixteen sequences are formed by combining one of the ordinal sequences from Fig. 4-7 with one of the temporal sequences from Fig. 4-8. Experiment 2 only made use of the nine sequences involving Ord1, Ord2, Ord3, Temp1, Temp2, and Temp3, while Experiment 3 made use of all sixteen sequences.

4.3.3 Results

Results for Experiment 2 Ordinal, Temporal and Combined blocks are shown, respectively, in Figures 4-10, 4-11, & 4-12.

Experiment 2 Ordinal Block Results

Figure 4-10 shows the results of Experiment 2 Ordinal Block. Fig. 4-10A shows the number of ordinal errors averaged across the 13 subjects for the 30 trials of each condition. A two-way ANOVA, with condition and trial as factors, reveals a significant effect of both trial: $F(29,58) = 26.24$, $p << 0.0001$; and condition: $F(2,58) = 172.63$, $p << 0.0001$. From Fig. 4-10A, these two trends are visually obvious. As in Experiment 1, it appears that the effect of trial is largely due to a general learning effect during the first half of the block, trials 1-15. A two-way ANOVA on trials 1-15 reveals a strong effect of both condition: $F(2,28) = 51.32$, $p << 0.0001$; and trial: $F(14,28) = 22.36$ $p << 0.0001$. However, a two-way ANOVA on trials 16-30, the last half, reveals that the effect of condition remains significant: $F(2,28) = 178.91$, $p << 0.0001$; while the effect of trial is no longer significant: $F(14,28) = 1.04$, $p = 0.44$.

Figure 4-10B shows a bar graph generated by averaging across trials 16-30 of Fig. 4-10A. This bar graph follows the same trend seen in Experiment 1 (see Fig. 4-5): condition AH results in the lowest ordinal error, while condition A results in the highest ordinal error with condition H in the middle. Upon closer comparison of these two results, it is observed that the scale is similar amongst both results: condition AH results in an error of approximately 0.25 (0.23 in Exp. 1, 0.26 in Exp. 2), condition A results in a significantly higher error closer to 1 (0.71 in Exp. 1, 1.16 in Exp. 2), and condition H is close to 0.5 (0.43 in Exp. 1, 0.55 in Exp. 2). The consistency of these results across the two experiments lends further support to our hypothesis that haptic guidance can facilitate the playback of a rhythm musical sequence when learning to play. One-way ANOVAs performed on the bar graph data in Fig. 4-10B revealed significant differences between all conditions: for conditions AH and A: $F(1,28) = 342.45$, $p << 0.0001$; for conditions AH and H: $F(1,28) = 30.87$, $p << 0.0001$; and for condition A and H: $F(1,28) = 169.13$, $p << 0.0001$.

Figures 4-10C & D show timing data for the Experiment 2 Ordinal Block. Since all the note lengths in this block were 500 ms in duration, we might not necessarily expect

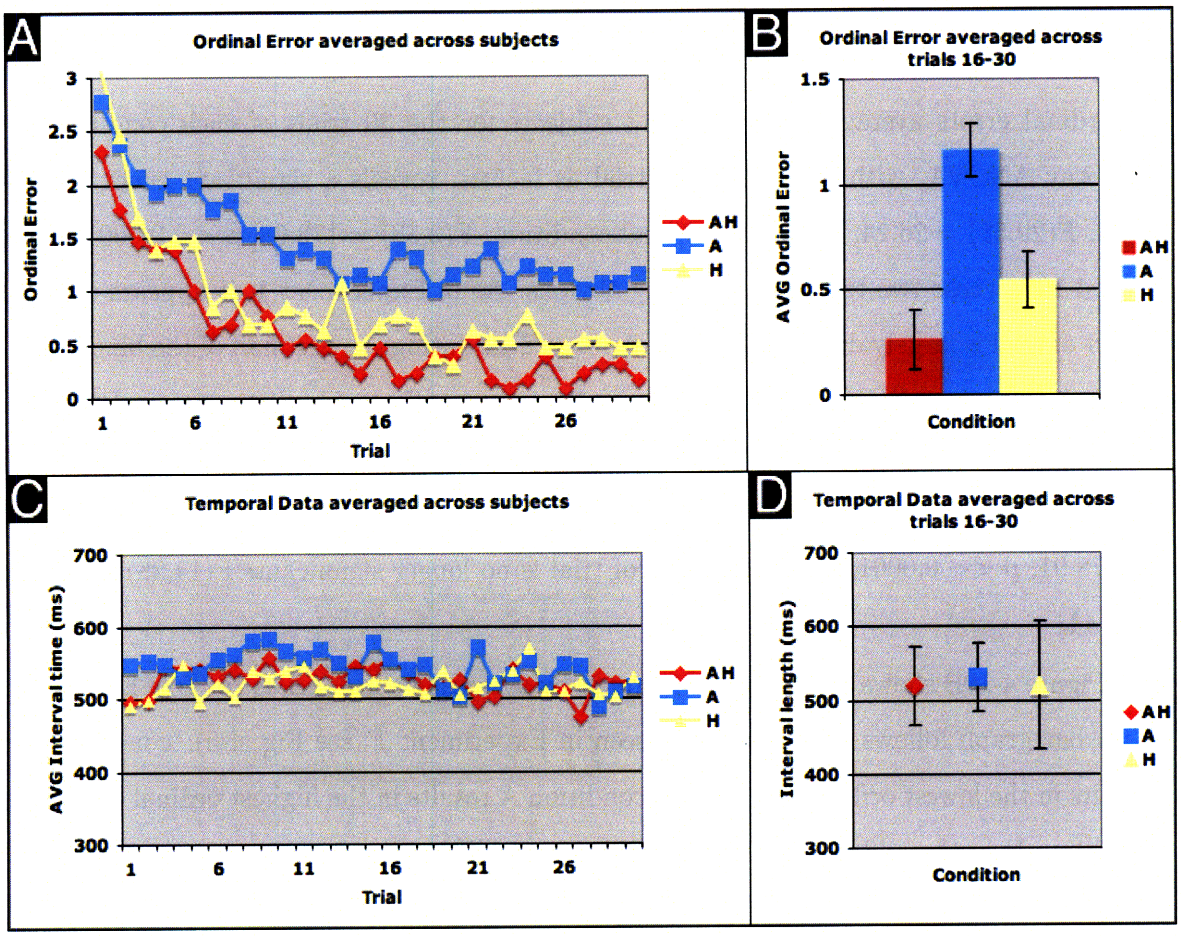

Figure 4-10: Experiment 2 Ordinal Block Results. Panels A shows ordinal error average across (N = 13) subjects and plotted by trial for each condition. Panel B is a bar graph of the average of trials 16-30 in panel A. Panel C shows temporal measurements for the sequence, averaged across subject and plotted by trial for each condition. Panel D is an average of trials 16-30 in Panel C. Error bars are standard deviation.

to see significant differences between conditions due to the lack of difficulty. Indeed, this is what is observed: Fig. 4-10C shows interval size averaged across sequence (there are 5 intervals per sequence) and across subject, while Fig. 4-10D shows the average across trials 16-30. Visual inspection indicates no significant difference across condition or trial. This is confirmed by a two-way ANOVA (trial x condition) performed on the temporal data from trials 16-30, which did not reveal a significant effect of either trial: $F(14,28) = 1.07$, $p = 0.419$, or condition: $F(2,28) = 1.68$, $p = 0.20$.

Temporal Block

Figure 4-11 shows the results of Experiment 2 Temporal Block. Fig. 4-11A shows the number of ordinal errors averaged across the 13 subjects for the 30 trials of each condition. Since the sequences used in this block only varied in the temporal, but not ordinal domain, the number of ordinal errors should be near zero. As expected, Fig. 4-11A shows minimal ordinal error.

Figure 4-11B-H show the temporal data for Experiment 2 Temporal Block. Fig. 4-11B shows the measured temporal intervals, averaged across subject for each condition. A separate line for each interval size is plotted, corresponding to the three interval sizes in each rhythm: 250ms , 500ms, and 750ms. The 250 ms line is computed from the average of the three 250 ms intervals in the sequence. From visual inspection, it appears that the 250ms interval is fairly well replicated, while there is a good degree of noise in the data for the 500 ms and 750 ms intervals; they seem to cluster in an area between 500 ms and 700 ms, with no clear distinction between the two groups of interval size. To parse these data, the last 15 trials were processed in two different ways. Fig. 4-11C-E shows the timing data processed in absolute time (in milliseconds), while Fig. 4-11F-H shows the timing data processed in terms of the ratios of intervals (see Experiment 2 Data Analysis section for further reference).

Fig. 4-11C shows an X-Y plot of the average timing interval values for the last 15 trials of the block. Measured interval time is plotted against the target interval time. As can be seen, the 250 ms has an average above 250 ms, the 500 ms interval is consistently overestimated, and the 750 ms interval is consistently underestimated. Temporal error is calculated by taking the absolute value of the difference between actual interval size and the target interval size. Temporal error across the 30 trials in shown in Fig. 4-11D, and the average of the last 15 trials is shown in Fig. 4-11E. A two-way ANOVA (trial x condition) on these data (last 15 trials) revealed a significant effect of condition: $F(2,28) = 15.75$, $p < 0.0001$, but not trial: $F(14,28) = 0.94$, $p = 0.53$. A closer inspection of Fig. 4-11C reveals that the 250 ms interval for condition H has a slightly higher value than those for the other two conditions. The larger size of the root interval, the 250 ms interval, could the be the cause for the higher temporal error in condition H. Since a rhythmic pattern can be played at different tempos, it is possible that, when analyzed with respect to the generated ratio between intervals, we might see a different result.

Fig. 4-11F shows an X-Y plot of the temporal data when expressed in terms of its ratio. In this analysis, the 500 ms and 750 ms intervals in each trial of the experiment are divided by the average of the three 250 ms intervals in that particular trial. Therefore, in the analysis, the error in the smallest interval, the 250 ms interval, is disregarded. This type of analysis is done to account for situations where the rhythm is played correctly at a tempo different for the target tempo. In Fig. 4-11F, we see that the 2:1 ratio interval (the 500 ms interval), is closer to the black "target" line than in the absolute timing analysis (Fig. 4-11C). However, the 3:1 ratio seems to deviate further from the ideal line than in the absolute timing case. When we take the difference in ratio and plot them, we get Fig. 4-11, which shows the timing error, in terms of a ratio timing analysis, plotted for the three conditions over the 30 trials. Fig. 4-11H shows an average of these data for the last 15 trials. A two-way ANOVA on this data set reveals the same trend as seen with the absolute timing analysis: a significant effect of condition, $F(2,28) = 37.51$, $p << 0.0001$, with no effect of trial, $F(14,28) = 0.707$, $p = 0.75$. Visual inspection of Fig. 4-11D & E reveals that condition results in a higher amount of temporal error than conditions AH & A.

Combined Block

Ordinal Data Figure 4-12 shows the results of Experiment 2 Combined Block. In this block, subjects learned rhythmic sequences which were composed of an ordinal and temporal pattern which they learned in the prior two blocks. All stimuli in the Combined block were tested under the condition A. Fig. 4-12A shows the number of ordinal errors averaged across the 13 subjects for the 30 trials of each condition. A two-way ANOVA, with condition and trial as factors, reveals a significant effect of both trial, $F(29,58) = 5.01$, $p << 0.0001$, and condition, $F(2,58) = 39.06$, $p << 0.0001$. From Fig. 4-12A, these two trends are visually

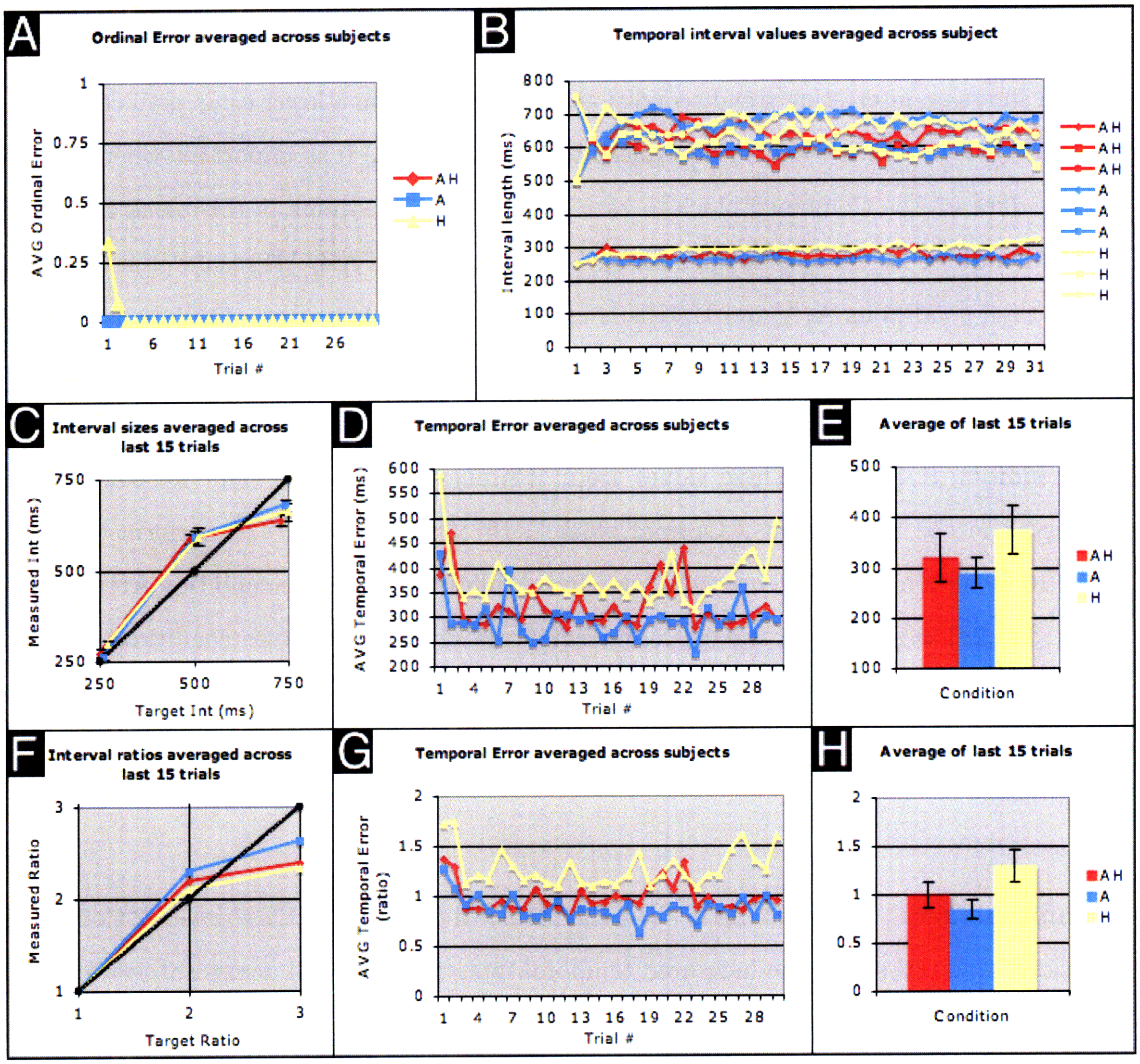

Figure 4-11: Experiment 2 Temporal Block Results. Panel A shows ordinal error average across (N = 13) subjects and plotted by trial for each condition. Panel B shows measurements for each temporal interval in the sequence, averaged across subject and plotted by trial for each condition. Panels C-E show temporal data processed with respect to absolute timing, while panels F-H show temporal data processed with respect to ratio timing (see text for description). Error bars are standard deviation.

obvious. As we've seen before, effect of trial represents the general learning effect during the first half of the block, trials 1-15. A two-way ANOVA on trials 16-30 reveals that the effect of condition remains significant, $F(2,28) = 73.89$, $p << 0.0001$, while the effect of trial is not significant, $F(14,28) = 0.81$, $p = 0.65$.

Also in Figure 4-12A is a bar graph generated by averaging across trials 16-30. This bar graph shows an interesting trend: condition AH/AH results in a lower error than conditions A/A and H/H, which result in equivalent amounts of error. It is important when looking at the data for the Combined block to keep in mind that all stimuli in this block are tested under condition A. Therefore, the observation that condition AH/AH results in less ordinal error than conditions A/A and H/H is consistent with the hypothesis that the advantage from conditions AH in the earlier blocks transfers to performance in the Combined block. In this bar graph, the value for condition AH/AH is 1.02, for condition A/A, 1.56, and for condition H/H, 1.54. These values are in a similar range to the value for condition A observed in the Experiment 2 Ordinal block, 1.16. One-way ANOVAs performed on the trial 16-30 data in Fig. 4-12A revealed significant differences between condition AH/AH and A/A: $F(1,28) = 147.28$, $p << 0.0001$, and significant difference between conditions AH/AH and H/H: $F(1,28) = 113.09$, $p << 0.0001$, but no significant difference between conditions A/A and H/H: $F(1,28) = 0.09$, $p = 0.77$. These results are consistent with the transfer hypothesis.

Temporal Data Figure 4-12B-F show the temporal data for the Experiment 2 Combined block. Fig. 4-12B shows the measured temporal intervals, averaged across subject for each condition. A separate line for each interval size is plotted, corresponding to the three interval sizes in each rhythm: 250ms , 500ms, and 750ms. From visual inspection, it appears that the 250ms interval is fairly well replicated, while there is a good degree of noise in the data for the 500 ms and 750 ms intervals. As before, the last 15 trials were processed in two different ways. Fig. 4-12C-D represents processing the timing data in absolute time, in milliseconds, while Fig. 4-12E-F represents processing the timing data in terms of the ratios of intervals (see Data Analysis section for further reference).

Fig. 4-12C shows an X-Y plot of the average timing interval values for the last 15 trials of the block. Measured interval time is plotted against the target interval time. As can be seen, the 500 ms interval is consistently overestimated, while the 750 ms interval is consistently underestimated. Temporal error is calculated by taking the absolute value of the difference between actual interval size and the target interval size. Temporal error across the 30 trials is shown in Fig. 4-12D, and the average of the last 15 trials is plotted in the bar graph. A two-way ANOVA (trial x condition) on these data (last 15 trials) revealed a significant effect of condition: $F(2,28) = 24.69$, $p < 0.0001$, but not trial: $F(14,28) = 0.95$, $p = 0.53$. One-way ANOVAs performed on the trial 16-30 data in Fig. 4-12D revealed significant differences between condition AH/AH and A/A: $F(1,28) = 25.97$, $p < 0.0001$, and significant difference between conditions A/A and H/H: $F(1,28) = 38.98$, $p << 0.0001$, but no significant difference between conditions AH/AH and H/H: $F(1,28) = 0.51$, $p = 0.48$. It appears that the significant effect of condition is due to the higher amount of temporal error seen in condition A/A.

When the temporal data are analyzed with regards to ratio timing, a similar overall trend is observed. Fig. 4-12E shows an X-Y plot of the temporal data when expressed in terms of its ratio. In Fig. 4-12E, we see that the 2:1 ratio interval (the 500 ms interval), is closer to the black "target" line than in the absolute timing analysis (Fig. 4-12C). Given that the average size of the 1:1 ratio interval is generally larger than 250 ms, this could represent the fact that subjects are able to replicate the 2:1 ratio interval correctly with regards to the size of the base interval. However, the 3:1 ratio seems to deviate further from the ideal line than in the absolute timing case. In Fig. 4-12E, the values for the third interval are very close to those of the second interval, suggesting that subjects were not successful at replicating the third interval, but instead approximated an interval size closer to that seen for the 2:1 interval. Fig. 4-12F shows the temporal error calculated as the amount of deviation from the black target line for all 30 trials. The average for the last 15 trials is also shown. One-way ANOVAs performed on the trial 16-30 data in Fig. 4-12D revealed significant differences between condition AH/AH and A/A: $F(1,28) = 13.86$, $p < 0.001$, and significant difference between conditions A/A and H/H: $F(1,28) = 16.21$, $p < 0.001$, but no significant difference between conditions AH/AH and H/H: $F(1,28) = 0.49$, $p = 0.49$. Both forms of timing analysis, absolute timing and ratio timing, indicate a slightly worse timing performance for condition A in the Combined block. In the ratio timing analysis, the increased temporal error for condition A/A is most noticeable during the latter half of trials, 16-30.

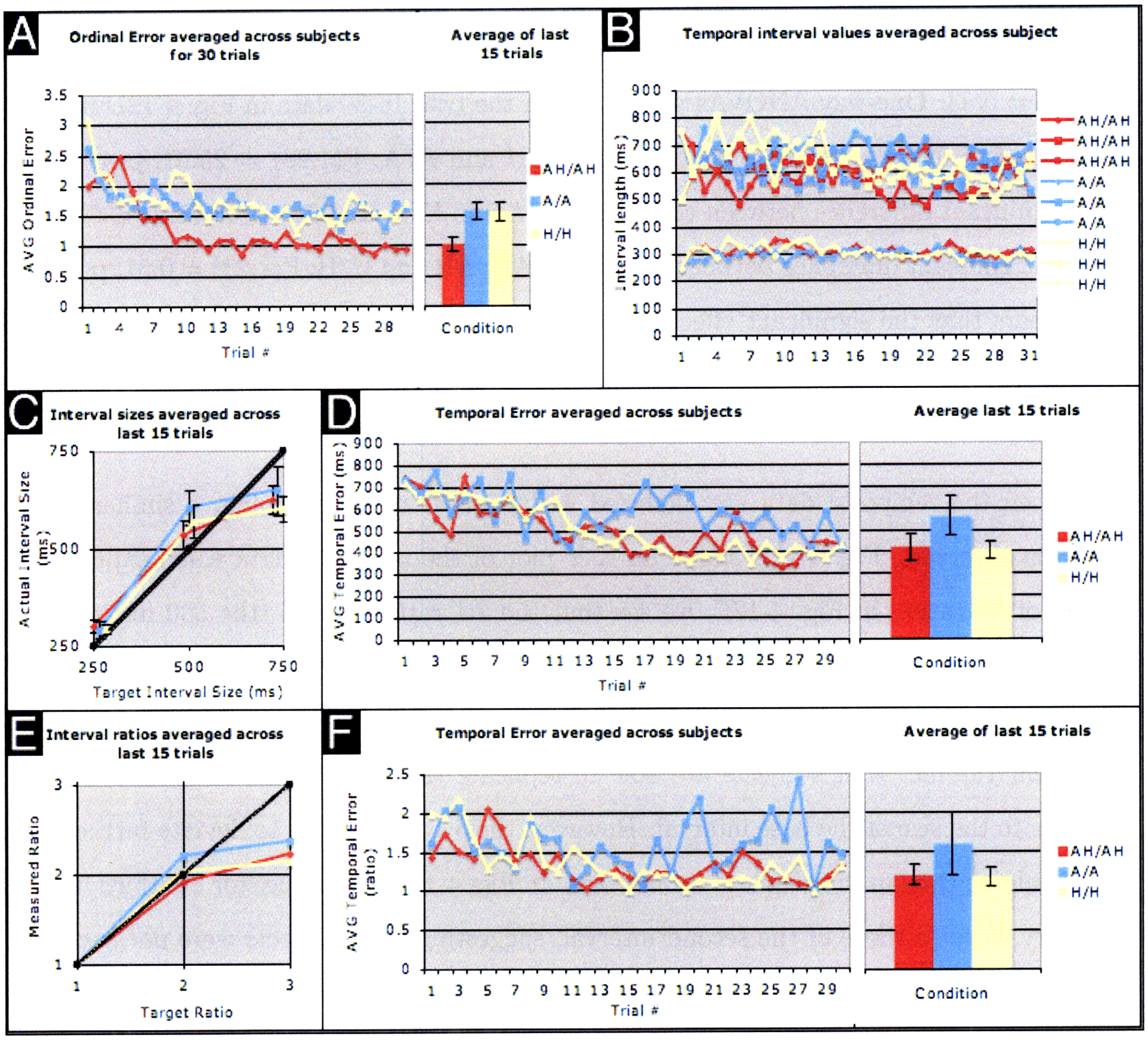

Figure 4-12: Experiment 2 Combined Block Results. Panel A shows ordinal error average across (N = 13) subjects and plotted by trial for each condition, along with a bar graph of the average of trials 16-30. Panel B shows measurements for each temporal interval in the sequence, averaged across subject and plotted by trial for each condition. Panels C-D show temporal data processed with respect to absolute timing, while panels E-F show temporal data processed with respect to ratio timing (see text for description). Error bars are standard deviation.

4.3.4 Summary & Discussion

Experiment 2 was designed to probe deeper into understanding how haptic guidance can facilitate rhythmic motor learning. In order to do this, three separate blocks of learning were designed. Experiment 2 Ordinal Block (Fig. 4-10) consisted of learning three stimuli that only varied in the note order (ordinal domain), but not in time (temporal domain), under the three experimental conditions: AH, A, & H. The results of this block provide insight into the effect of haptic guidance on ordinal sequence learning. Experiment 2 Temporal Block (Fig. 4-11) consisted of learning three stimuli that only varied in time (temporal domain), but not note order (ordinal domain), under the three experimental conditions: AH, A, & H. The results of the Temporal block provide a glimpse of the effect of haptic guidance on temporal sequence learning. The final block, the Combined block, was designed as a transfer test to probe how the advantageous effects of haptic guidance, as gained during the Ordinal and Temporal blocks, transfer to learning new rhythmic sequences.

Experiment 2 Ordinal Block The results from Experiment 2 Ordinal Block (Fig. 4-10A-B) follow the same trend seen during Experiment 1. Performance in condition AH resulted in the smallest amount of ordinal error (0.27), condition H had slightly more error (0.55), and condition A resulted in the highest error (1.16). As with Experiment 1, these data support the hypothesis that haptic guidance can facilitate the learning of a rhythmic motor sequence, in particular learning the ordinal property of a sequence. Timing data from the Ordinal block (Fig. 4-10C-D) did not indicate any difference between conditions for timing performance. Average interval lengths were slightly more than 500 ms for all conditions (Fig. 4-10D).

Experiment 2 Temporal Block Results from the Temporal block of Experiment 2 (Fig. 4-11) indicate that subjects are slightly worse under condition H than under conditions AH and A. These results suggest that haptic guidance does not provide an advantage for learning the relatively simple temporal patterns used in the Temporal block. One possible explanation for this result might be that the task does not present enough difficulty for subjects to benefit from haptic guidance. This result is similar to what was seen in the haptic guidance studies of Feygin *et al.* [61] and Liu *et al.* [62]. In those studies, haptic guidance alone resulted in worse performance than visual-only or visual + haptic learning.

Similarly in Experiment 2 Temporal block, condition H results in worse performance than audio-only and audio + haptic learning. Perhaps the reason a haptic guidance advantage is not seen in this block is that the mechanisms involved in audio-only learning are sufficient for learning the simple 6-note patterns used in the Temporal Block, such that the addition of haptic information is not useful. This does not rule out the possible role of haptic guidance in facilitating temporal learning, but instead just shows that our paradigm is not sufficient at elucidating the effect. Perhaps if the temporal patterns were more complex, such as syncopated rhythms, we might see a different result. Alternatively, another area in which haptic guidance might facilitate purely temporal learning would be in the coordination of the different hands. Syncopation and coordination could be a fruitful area of research for investigating the effects of haptic guidance on temporal learning.

Experiment 2 Combined Block In the Combined block, subjects learned 3 sequences which varied in both temporal and ordinal domains. These three stimuli were all presented using just audio, like condition A of Experiment 2 Ordinal Block and Experiment 1. The stimuli, however, were designed for each subject so that the ordinal and temporal patterns of the combined sequence were learned separately under the same experimental conditions in the Ordinal and Temporal blocks. The stimuli were designed as such to test the transfer effect of haptic guidance. If haptic guidance confers an advantage in ordinal and/or temporal learning, then this advantage might extend to learning a new rhythmic sequence when that sequence is composed of ordinal and temporal patterns learned with haptic guidance. However, if there is no transfer, then we would expect to see equivalent performance across the three stimuli in the Combined block, since they are all tested under condition A.

Results from the Combined block of Experiment 2 (Fig. 4-12) show less ordinal error (better performance) for condition AH/AH (1.02) than for conditions A/A (1.56) & H/H (1.54), which were equivalent. These data suggest that the advantageous effects of haptic guidance seen in the earlier blocks, at least the Ordinal block, do indeed transfer to learning a new rhythmic sequence. However, the haptic guidance advantage only transfers for sequences trained on condition AH in the prior blocks; the advantage seen for condition H in the Ordinal block does not transfer, as the values in the Combined block for conditions A/A & H/H are equivalent. Comparing the scale of these measurements, we see that the error measurements from the Combined block (1.0,1.5) are in the range of the error measurements from Ordinal block condition A results. With regards to timing, there appears to be slightly less error for conditions AH/AH & H/H.

In summary, these results confirm the advantageous effects of haptic guidance in an auditory-motor learning task of rhythmic motor sequences. Specifically, haptic guidance facilitated better performance (less error) in ordinal learning. Additionally, the haptic guidance advantage appeared to facilitate better performance in a transfer test in which a new rhythmic sequence is learned. While it is clear that haptic guidance results in an advantage during ordinal sequence learning, as demonstrated in Experiment 2 Ordinal block, it is not clear how haptic guidance independently affects the transfer of ordinal and temporal learning. Is the transfer effect for condition AH/AH in the Combined block due to training the ordinal pattern under condition AH, the temporal pattern under condition AH, or both? Experiment 3 will attempt to answer this question.

4.4 Experiment 3

4.4.1 Background

In Experiment 2, we saw that haptic guidance facilitated learning of the ordinal pattern of a sequence, and that this advantage transferred to learning a new rhythmic sequence, as confirmed by the results of Experiment 2 Combined Block. While it is tempting to conclude that the better performance for condition AH/AH in the Combined block is due to the advantage gained in condition AH during the Ordinal block, we must be careful. Condition AH/AH did result in less ordinal error in the Combined block. However, whether this effect is due to a combined advantage of training both ordinal and temporal patterns under condition AH, or solely to training the ordinal pattern under condition AH, is not yet clear.

Experiment 3 was designed to further elucidate how haptic guidance can modulate the transfer of ordinal and temporal sequence learning. Experiment 3 is very similar to Experiment 2 in that subjects executed 3 blocks: Ordinal, Temporal and Combined. However, in Experiment 3 Combined Block, subjects test two new conditions: AH/A, which is a sequence in which the ordinal pattern was trained under condition AH and the temporal pattern was trained under condition A, and condition A/AH, which is a sequence in which the ordinal pattern was trained under condition A and the temporal pattern was trained under condition AH. These two conditions were tested along with conditions AH/AH and A/A. In Experiment 3 Ordinal Block, subjects tested two sequences under condition AH and two sequences under condition A. In Experiment 3 Temporal Block, subjects also tested two sequences under condition AH and two under condition A. Condition H was not used in Experiment 3. Finally, in Experiment 3 Combined Block, subjects tested sequences under the four conditions: AH/AH, AH/A, A/AH, and A/A [5].

Experiment 3 also tested retention effects by having twelve subjects return to the lab the next day to complete Experiment 3 Retention Block, which is a repetition of the Combined block from the day before, with the stimulus order rearranged.

[5]Conditions are always described as Ordinal/Temporal (O/T)

4.4.2 Methods

Subjects

Sixteen subjects (N=16) participated in this experiment, ranging in age from 20 to 51 years old, with a mean of 27.5 years of age. All subjects were right-handed, and reported having little to no formal piano training. Subjects participated in the experiment by completing a 90-minute session in our lab, and were compensated financially for their participation. Twelve subject (N=12) also returned to the lab within 20-28 hours of the initial visit for a 30 minute followup session, for which they were additionally compensated. The experimental protocol was approved by the MIT Committee On the Use of Humans and Experimental Subjects, under COUHES protocol #0708002363. Informed consent was obtained from all subjects prior to beginning the experiment.

Behavioral paradigm

Figure 4-13 shows a schematic of the behavioral paradigm used in Experiment 3. For the first day's session, the behavioral paradigm was very similar to Experiment 2, in that subjects executed three blocks of learning: Ordinal, Temporal, and Combined. However, in Experiment 3, four sequences were tested in each block. In the Ordinal block, two sequences were tested under condition AH, and two sequences were tested under condition A. In the Temporal block, two sequences were tested under condition AH, and two sequences were tested under condition A. In the Combined block, the ordinal and temporal sequences were combined to form four new sequences which corresponded to the following conditions:

1. **AH/AH**: Target sequence consists of an ordinal and temporal pattern that were each trained under condition AH in the prior Ordinal and Temporal blocks. Target sequence presented using only audio.

2. **AH/A**: Target sequence consists of an ordinal trained under condition AH in the prior Ordinal block, and a temporal pattern trained under condition A in the prior Temporal block. Target sequence presented using only audio.

3. **A/AH**: Target sequence consists of an ordinal trained under condition A in the prior Ordinal block, and a temporal pattern trained under condition AH in the prior Temporal block. Target sequence presented using only audio.

4. **A/A**: Target sequence consists of an ordinal and temporal pattern that were each trained under condition A in the prior Ordinal and Temporal blocks. Target sequence presented using only audio.

Twelve subjects also returned to the laboratory between 20-28 hours after the initial visit, and executed a Retention block. The Retention block was identical to the Combined block that the subject had run before, except that the stimulus presentation order had been rearranged.

Data Analysis

All data analysis in Experiment 3 is identical to the data analysis methods used for Experiment 2. The reader is referred to the Experiment 2 Methods section for further reading.

4.4.3 Results

Ordinal Block

Figure 4-14 shows the results of Experiment 3 Ordinal Block. Fig. 4-14A shows the number of ordinal errors averaged across the 16 subjects for the 30 trials of each condition. Since both conditions (AH & A) were run twice, four lines are plotted. The runs of each condition were averaged across together (not shown), and analyzed with a two-way ANOVA (condition x trial), which revealed a significant effect of both trial: $F(29,29) = 26.66$, $p << 0.0001$; and condition: $F(1,29) = 1630.20$, $p << 0.0001$. As we saw before, these two trends are visually obvious, and it appears that the effect of trial is largely due to a general learning effect during the first half of the block, trials 1-15. A two-way ANOVA on trials 1-15 reveals a strong effect of both condition: $F(1,14) = 684.59$, $p << 0.0001$; and trial: $F(14,14) = 31.63$, $p << 0.0001$. However, a two-way ANOVA on trials 16-30 reveals that the effect of condition remains significant: $F(1,14) = 1260.84$, $p << 0.0001$; while the effect of trial is no longer significant: $F(14,14) = 1.20$, $p = 0.37$.

Figure 4-14B shows a bar graph generated by averaging across trials 16-30 for both runs of each condition. This bar graph follows the same trend seen in Experiment 1 and in Experiment 2 Ordinal block: condition AH results in significantly lower ordinal error than condition A. The scale is similar, as well: condition AH results in an error value of approximately 0.19 (Exp. 1: 0.23, Exp. 2 Ord: 0.26), while condition A results in a

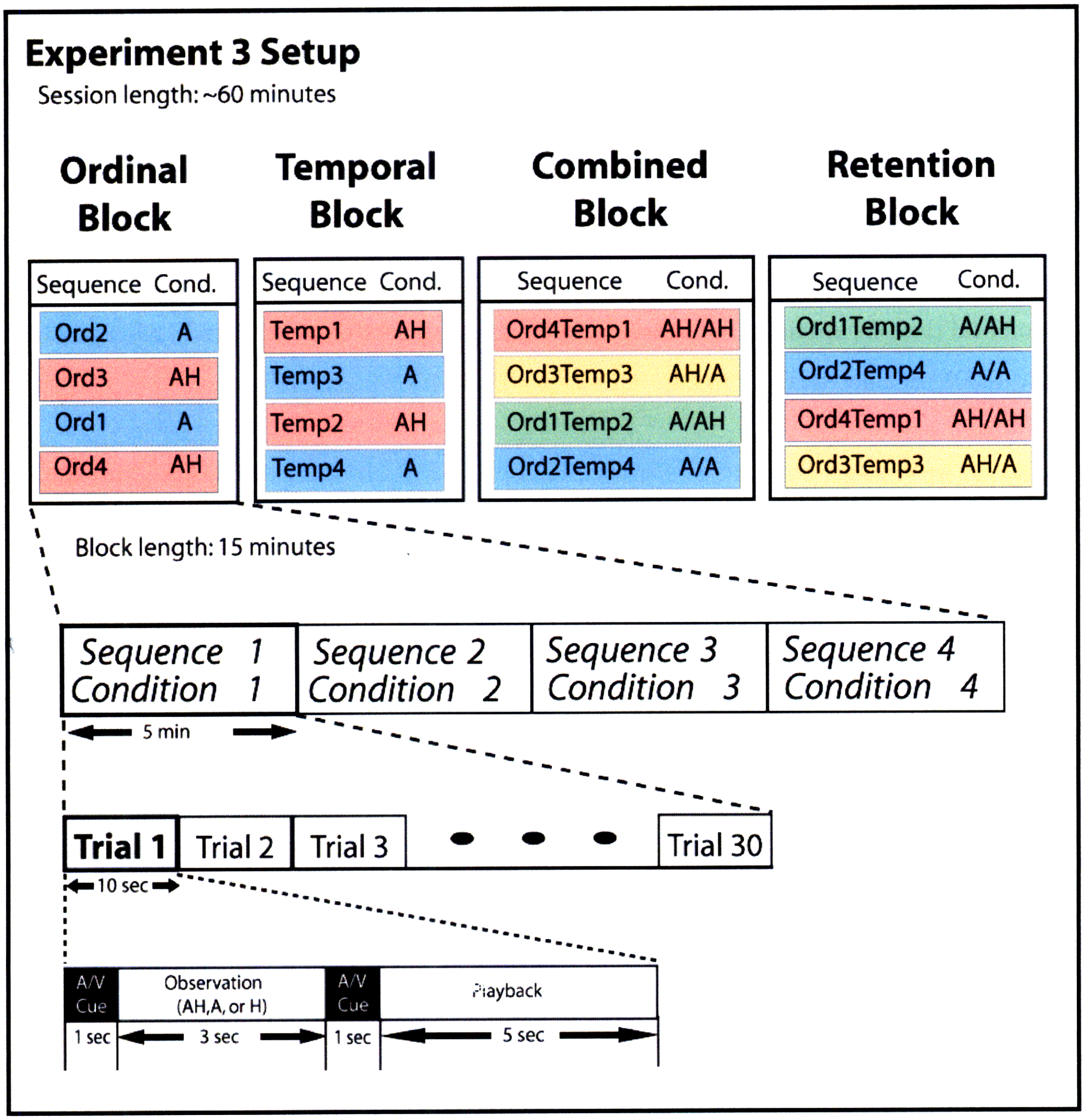

Figure 4-13: Experiment 3 behavioral paradigm. Sixteen subjects (N=16) tested three blocks of learning: Ordinal, Temporal and Combined, similar to Experiment 2. In addition, twelve subjects (N=12) returned the next day to complete a Retention block. In each block, a different sequence was tested under a different condition. Refer to text for description of conditions, and to Figs. 4-7,4-8, and 4-9 for descriptions of target sequences.

significantly higher error of 1.28 (Exp. 1: 0.71, Exp. 2 Ord: 1.16). The consistency of these results across the experiments gives confidence to our hypothesis that haptic guidance can facilitate the playback of a rhythmic musical sequence when a subject is learning to play.

Figures 4-14C & D show timing data for Experiment 3 Ordinal Block. Since all the note lengths in this experiment were 500 ms in duration, significant differences between conditions are not expected. Indeed, this is what is observed: Fig. 4-14C shows interval size averaged across sequence (there are 5 intervals per sequence) and across subject for the four blocks, while Fig. 4-14D shows a graph generated by average across trials 16-30 for both runs of each condition. A one-way ANOVA (trial x condition) performed on the averaged temporal data from trials 16-30 revealed a significant effect of condition: $F(1,14) = 23.82$, $p < 0.001$, but not trial: $F(14,14) = 1.40$, $p = 0.27$.

Temporal Block

Figure 4-15 shows the results of the Experiment 3 Temporal Block. Fig. 4-15A shows the number of ordinal errors averaged across the 16 subjects for the 30 trials of each condition. Since the stimulus sequences used in this block only varied in the temporal, but not ordinal domain, the number of ordinal errors should be near zero. As expected, Fig. 4-15A shows minimal ordinal error.

Figure 4-15B-H show the temporal data for the Experiment 3 temporal block. Fig. 4-15B shows the measured temporal intervals, averaged across subject for each condition. A separate line for each interval size is plotted, corresponding to the three interval sizes in each rhythm: 250ms , 500ms, and 750ms. From visual inspection, it appears that the 250ms interval is fairly well replicated, while there is a good degree of noise in the data for the 500 ms and 750 ms intervals. To parse apart these data, the last 15 trials was processed in two different ways. Fig. 4-15C-E represents processing the timing data in absolute time, in milliseconds, while Fig. 4-15F-H represents processing the timing data in terms of the ratios of intervals (see Data Analysis section for further reference).

Fig. 4-15C shows an X-Y plot of the average timing interval values for the last 15 trials of the block. Measured interval time is plotted against the target interval time. As can be seen, the 500 ms interval is consistently overestimated, while the 750 ms interval is consistently underestimated. Temporal error is calculated by taking the absolute value of the difference between actual interval size and the target interval size. Temporal error

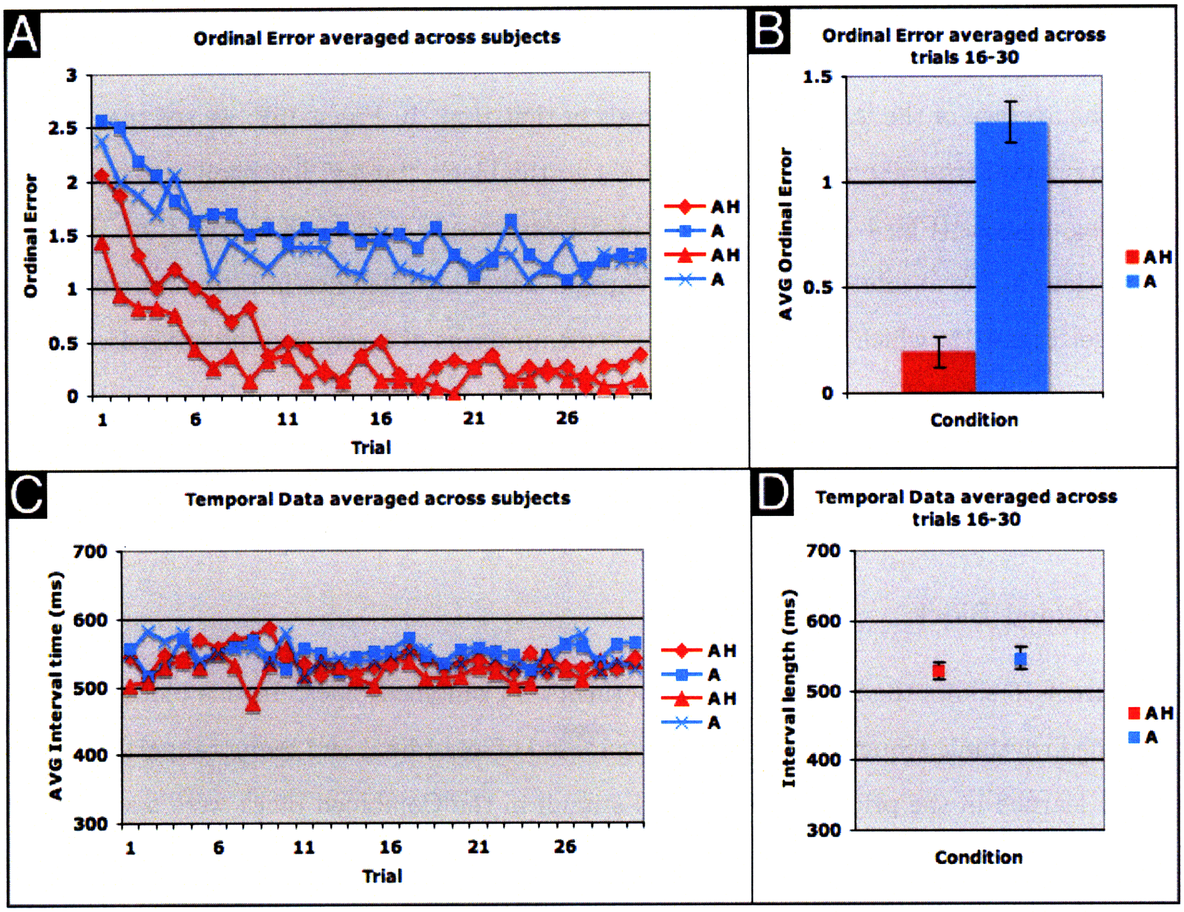

Figure 4-14: Experiment 3 Ordinal Block Results. Panels A shows ordinal error average across (N = 16) subjects and plotted by trial for both runs of each condition. Panel B is a bar graph taken by first averaging like conditions together in panel A, and then averaging trials 16-30. Panel C shows temporal measurements for the sequence, averaged across subject and plotted by trial for each condition. Panel D is an average of condition and trials 16-30 in Panel C. Error bars are standard deviation.

across the 30 trials in shown in Fig. 4-15D, and the average of the last 15 trials is shown in Fig. 4-15E. A two-way ANOVA (trial x condition) on these data (last 15 trials) revealed no significant effect of condition: $F(1,14) = 0.04$, $p = 0.85$, or trial: $F(14,14) = 1.86$, $p = 0.13$. This result is similar to the Experiment 2 Temporal block (see Fig. 4-11E), where the temporal error values for conditions AH and A were also equivalent, in the range of 300 ms.

Fig. 4-15F shows an X-Y plot of the temporal data when expressed in terms of its ratio. In this analysis, the 500 ms and 750 ms intervals in each trial of the experiment are divided by the average of the three 250 ms intervals in that trial. In Fig. 4-15F, we see that the 2:1 ratio interval (the 500 ms interval), is closer to the black "target" line than in the absolute timing analysis (Fig. 4-15C). However, the 3:1 ratio seems to deviate further from the ideal line than in the absolute timing case. When we take the difference in ratio and plot them, we get Fig. 4-15, which shows the timing error, in terms of a ratio timing analysis, plotted for the three conditions over the 30 trials. Fig. 4-15H shows an average of these data for the last 15 trials. A two-way ANOVA on this data set reveals a significant effect of condition: $F(1,14) = 25.33$, $p < 0.001$, with no effect of trial, $F(14,14) = 1.33$, $p = 0.30$.

Combined Block

Figure 4-16 shows the results of the Experiment 3 Combined block. In this block, subjects learned rhythmic sequences which were composed of an ordinal and temporal pattern which they learned in the prior two blocks. All stimuli in the Combined block were tested under the condition A.

Ordinal Data Fig. 4-16A shows the number of ordinal errors averaged across the 16 subjects for the 30 trials of each condition. A two-way ANOVA, with condition and trial as factors, reveals a significant effect of both trial, $F(29,87) = 18.75$, $p << 0.0001$, and condition, $F(3,87) = 114.72$, $p << 0.0001$. As before, these two trends are visually obvious from Fig. 4-16A. As we've seen before, effect of trial represents the general learning effect during the first half of the block, trials 1-15. A two-way ANOVA on trials 16-30 reveals that the effect of condition remains significant, $F(3,42) = 101.29$, $p << 0.0001$, while the effect of trial is not significant, $F(14,42) = 1.19$, $p = 0.32$.

Also in Figure 4-16A is a bar graph generated by averaging across trials 16-30. This bar graph shows a surprising trend: conditions AH/AH and AH/A, both condition in which

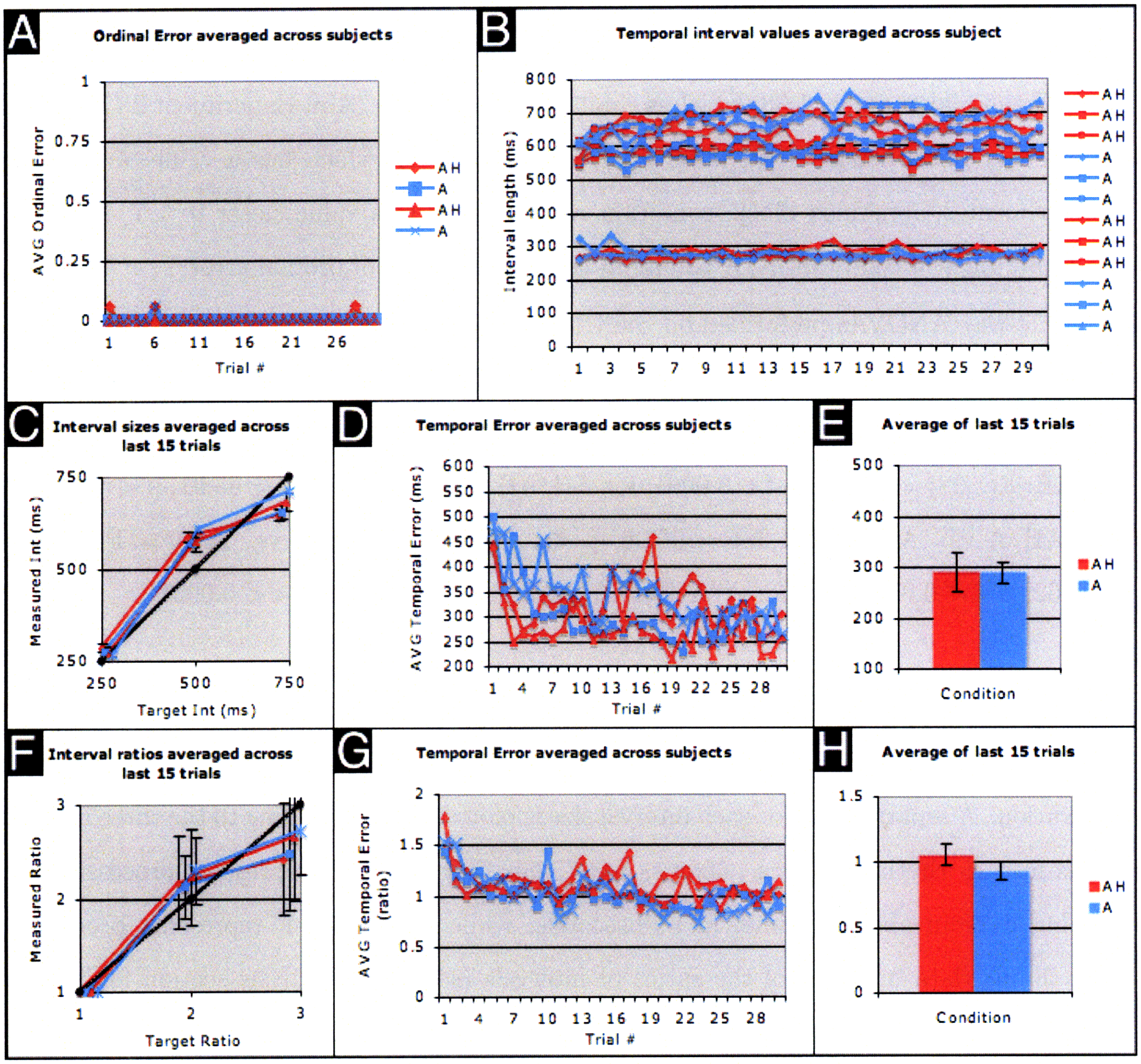

Figure 4-15: Experiment 3 Temporal Block Results. Panel A shows ordinal error average across (N = 16) subjects and plotted by trial for each condition. Panel B shows measurements for each temporal interval in the sequence, averaged across subject and plotted by trial for each condition. Panels C-E show temporal data processed with respect to absolute timing, while panels F-H show temporal data processed with respect to ratio timing (see text for description). Error bars are standard deviation.

the ordinal pattern was trained under AH, have similar values close to 1.0, while condition A/AH has a higher value closer to 1.5. Condition A/A, on the other hand, has a value below 0.5! The results for conditions AH/AH and AH/A are similar to those for condition AH in Experiment 2 Combined Block. This would make sense, as in all three conditions the ordinal component of the rhythm was trained under condition AH. The result for condition A/AH is a higher value, 1.38, which is similar to condition A/A in Experiment 2 Combined Block. The surprising result, however, is condition A/A, which has a value of 0.41. In Experiment 2 Combined block, condition A/A resulted in a value closer to 1.5. However, in Experiment 3 condition A/A results in the least amount of ordinal error.

One-way ANOVAs performed on the trial 16-30 data in Fig. 4-16A revealed significant contrasts between all conditions except between conditions AH/AH and AH/A: $F(1,28) = 0.12$, $p = 0.73$. The remaining contrasts were all statistically significant: for AH/AH vs. A/AH: $F(1,28) = 40.58$, $p \ll 0.0001$; for AH/AH vs. A/A: $F(1,28) = 65.91$, $p \ll 0.0001$; for AH/A vs. A/AH: $F(1,28) = 90.06$, $p \ll 0.0001$; for AH/A vs. A/A = $F(1,28) = 207.02$, $p \ll 0.0001$; and for A/AH vs. A/A: $F(1,28) = 315.38$, $p \ll 0.0001$.

Temporal Data Figure 4-16B-F show the temporal data for Experiment 3 Combined Block. Fig. 4-16B shows the measured temporal intervals, averaged across subject for each condition. A separate line for each interval size is plotted, corresponding to the three interval sizes in each rhythm: 250ms , 500ms, and 750ms. Fig. 4-16C-D represents processing the timing data in absolute time, in milliseconds, while Fig. 4-16E-F represents processing the timing data in terms of the ratios of intervals (see Data Analysis section for further reference).

Fig. 4-16C shows an X-Y plot of the average timing interval values for the last 15 trials of the block. Measured interval time is plotted against the target interval time. As can be seen, the 500 ms interval is consistently overestimated, while the 750 ms interval is consistently underestimated. Temporal error is calculated by taking the absolute value of the difference between actual interval size and the target interval size. Temporal error across the 30 trials in shown in Fig. 4-16D, and the average of the last 15 trials is plotted in the bar graph. A two-way ANOVA (trial x condition) on these data (last 15 trials) did not reveal a significant effect of condition: $F(3,42) = 3.99$, $p = 0.01$, or trial: $F(14,42) = 1.51$, $p = 0.15$.

When the temporal data is analyzed with regards to ratio timing, a similar overall trend is observed. Fig. 4-16E shows an X-Y plot of the temporal data when expressed in terms of its ratio. In Fig. 4-16E, we see that the 2:1 ratio interval (the 500 ms interval), is closer to the black "target" line than in the absolute timing analysis (Fig. 4-16C). Given that the average size of the 1:1 ratio interval is generally larger than 250 ms, this could represent the fact that subjects are able to replicate the 2:1 ratio interval correctly with regards to the size of the base interval. However, the 3:1 ratio seems to deviate further from the ideal line than in the absolute timing case. In Fig. 4-16E, the values for the third interval are very close to those of the second interval, suggesting that subjects were not successful at replicate the third interval, but instead approximated an interval size closer to that seen for the 2:1 interval. Fig. 4-16F shows the temporal error calculated as the amount of deviation from the black target line for all 30 trials. The average for the last 15 trials is also shown. A two-way ANOVA (trial x condition) on these data (last 15 trials) revealed a slightly significant effect of condition: $F(3,42) = 5.67$, $p = 0.0024$, but not trial: $F(14,42) = 1.42$, $p = 0.19$.

Retention Block

Ordinal Data Figure 4-17 shows the results of the Experiment 3 Retention block. This block was identical to Experiment 2 Retention block, except that the stimulus presentation order was rearranged. Fig. 4-17A shows the number of ordinal errors averaged across the 13 subjects for the 30 trials of each condition. A two-way ANOVA, with condition and trial as factors, reveals a significant effect of trial: $F(29,87) = 6.27$, $p << 0.0001$; but not condition: $F(3,87) = 2.79$, $p = 0.045$. However, when a two-way ANOVA is performed on these data for trials 16-30, a significant effect of condition is revealed: $F(3,42) = 20.68$, $p << 0.0001$; but no significant effect of trial: $F(14,42) = 1.60$, $p = 0.12$.

Also in Figure 4-17A is a bar graph generated by averaging across trials 16-30. This bar graph shows another surprising trend: conditions AH/AH and AH/A have similar values closer to 0.75, while conditions A/AH and A/A have values closer to 1.0.

These results maintain the trend seen in Experiment 3 Combined Block between conditions AH/AH, AH/A, and A/AH. However, now condition A/A exhibits a measure more similar to condition A/AH. The scale of these four results is a bit shifted from the scale of the Combined block. In the Retention block, the spread between the two AH-ordinal conditions (AH/AH, AH/A) and the two A-ordinal conditions (A/AH, A/A) is smaller:

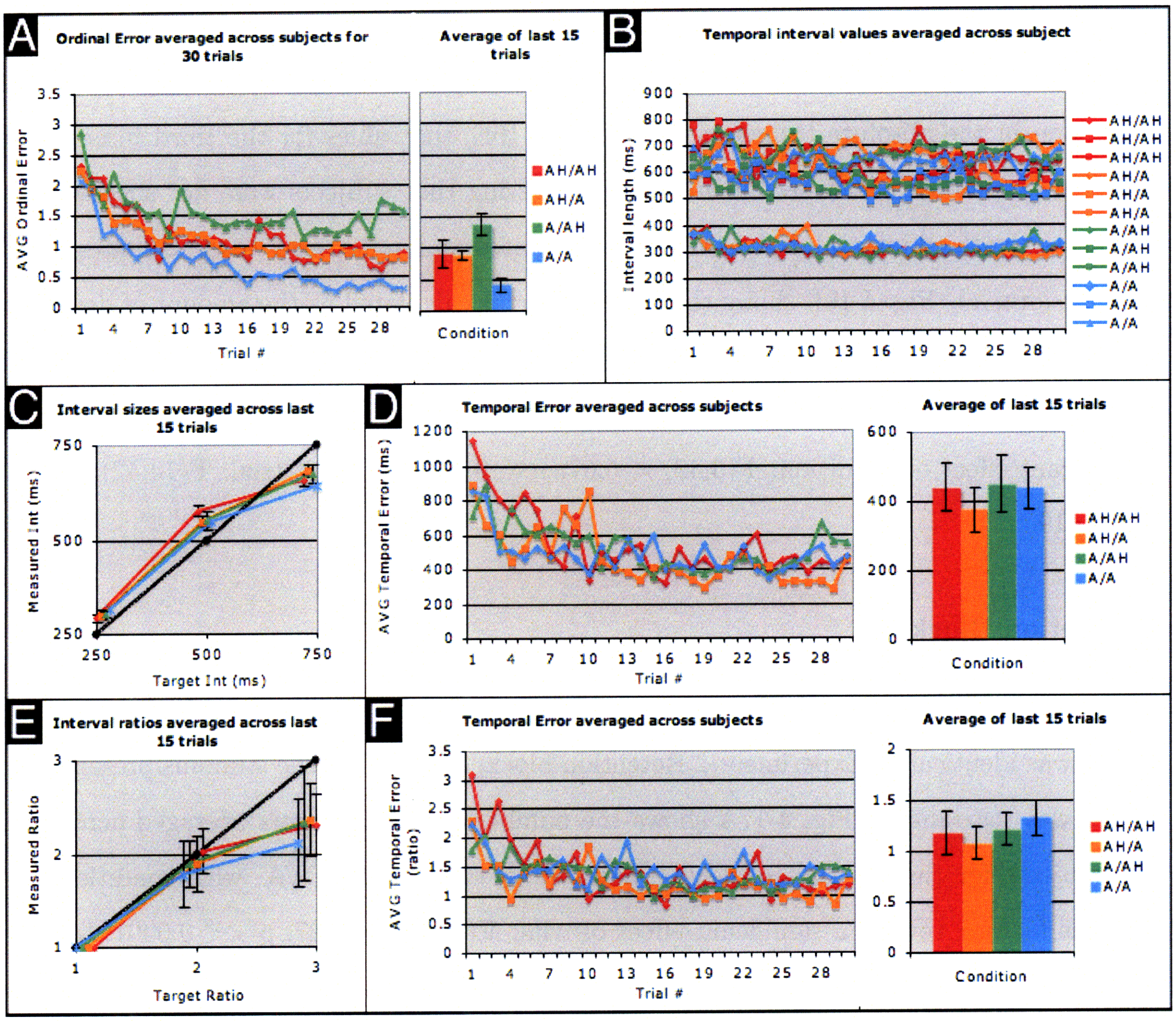

Figure 4-16: Experiment 3 Combined Block Results. Panel A shows ordinal error average across (N = 16) subjects and plotted by trial for each condition, along with a bar graph of the average of trials 16-30. Panel B shows measurements for each temporal interval in the sequence, averaged across subject and plotted by trial for each condition. Panels C-D show temporal data processed with respect to absolute timing, while panels E-F show temporal data processed with respect to ratio timing (see text for description). Error bars are standard deviation.

0.75 to 1.0, versus the spread in the Combined block between conditions AH/AH, AH/A, and A/AH: 1.0 to 1.5. One-way ANOVAs performed on the trial 16-30 data in Fig. 4-16A revealed significant contrasts between all conditions except between conditions AH/AH and AH/A: $F(1,28) = 5.68$, $p = 0.02$, and between conditions A/AH vs. A/A: $F(1,28) = 0$, $p = 1.0$. The remaining contrasts were all statistically significant: for AH/AH vs. A/AH: $F(1,28) = 16.94$, $p < 0.001$; for AH/AH vs. A/A: $F(1,28) = 17.61$, $p < 0.001$; for AH/A vs. A/AH: $F(1,28) = 31.59$, $p << 0.0001$; for AH/A vs. A/A: $F(1,28) = 32.51$, $p << 0.0001$.

Temporal Data Figure 4-17B-F show the temporal data for the Experiment 3 Retention block. Fig. 4-17B shows the measured temporal intervals, averaged across subject for each condition. A separate line for each interval size is plotted, corresponding to the three interval sizes in each rhythm: 250ms , 500ms, and 750ms. Fig. 4-17C-D represents processing the timing data in absolute time, in milliseconds, while Fig. 4-17E-F represents processing the timing data in terms of the ratios of intervals (see Data Analysis section for further reference).

Fig. 4-17C shows an X-Y plot of the average timing interval values for the last 15 trials of the block. Measured interval time is plotted against the target interval time. Temporal error is calculated by taking the absolute value of the difference between actual interval size and the target interval size. Temporal error across the 30 trials in shown in Fig. 4-17D, and the average of the last 15 trials is plotted in the bar graph. A two-way ANOVA (trial x condition) on these data (last 15 trials) revealed a significant effect of condition: $F(3,42) = 12.24$, $p < 0.0001$, but not trial: $F(14,42) = 1.08$, $p = 0.40$. One-way ANOVAs performed on the trial 16-30 data in Fig. 4-17D revealed significant contrasts between all conditions except between conditions AH/AH and AH/A: $F(1,28) = 0.87$, $p = 0.36$. The remaining contrasts were all statistically significant: for AH/AH vs. A/AH: $F(1,28) = 29.46$, $p < 0.0001$, for AH/AH vs. A/A: $F(1,28) = 0.55$, $p = 0.47$, for AH/A vs. A/AH: $F(1,28) = 34.39$, $p < 0.0001$, for AH/A vs. A/A: $F(1,28) = 2.51$, $p = 0.12$, and for A/AH vs. A/A: $F(1,28) = 18.64$, $p < 0.001$.

When the temporal data is analyzed with regards to ratio timing, a similar overall trend is observed. Fig. 4-17E shows an X-Y plot of the temporal data when expressed in terms of its ratio. In Fig. 4-17E, we see that the 2:1 ratio interval (the 500 ms interval), is closer to the black "target" line than in the absolute timing analysis (Fig. 4-17C). Given that the average size of the 1:1 ratio interval is generally larger than 250 ms, this could represent the fact that subjects are able to replicate the 2:1 ratio interval correctly with regards to the size of the base interval. However, the 3:1 ratio seems to deviate further from the ideal line than in the absolute timing case. In Fig. 4-17E, the values for the third interval are very close to those of the second interval, suggesting that subjects were not successful at replicate the third interval, but instead approximated an interval size closer to that seen for the 2:1 interval. Fig. 4-17F shows the temporal error calculated as the amount of deviation from the black target line for all 30 trials. The average for the last 15 trials is also shown. One-way ANOVAs performed on the trial 16-30 data in Fig. 4-17D revealed significant contrasts between all conditions except between conditions AH/AH and AH/A: $F(1,28) = 4.23$, $p = 0.049$. The remaining contrasts were all statistically significant: for AH/AH vs. A/AH: $F(1,28) = 19.83$, $p < 0.001$, for AH/AH vs. A/A: $F(1,28) = 0.25$, $p = 0.62$, for AH/A vs. A/AH: $F(1,28) = 39.47$, $p << 0.0001$, for AH/A vs. A/A: $F(1,28) = 5.93$, $p = 0.021$, and for A/AH vs. A/A: $F(1,28) = 13.62$, $p < 0.001$.

4.4.4 Summary & Discussion

Experiment 3 was designed to build on Experiment 2 by using the same transfer paradigm to probe deeper into understanding how haptic guidance, when independently applied to ordinal and temporal learning, facilitates rhythmic sequence learning. The same three blocks of learning were used as in Experiment 2, but the conditions changed. In the Ordinal and Temporal blocks of Experiment 3, subjects learned 4 rhythmic sequences: two in condition AH, and two in condition A. Condition H was not tested. Then, in the Combined block, the ordinal and temporal patterns were combined such that subjects tested two rhythmic sequences with ordinal/temporal components trained as AH/AH and A/A, but in addition two other combinations were tested: AH/A and A/AH. These two new combinations were designed to independently assess the effects of haptic guidance on the transfer of ordinal and temporal learning. In addition to the Combined block, 12 subject returned to the laboratory on the next day to run a Retention block, which comprised the same sequences and conditions as the Combined block the day before. The Retention block was designed to test whether or not the transfer effects of haptic guidance persist to the next day.

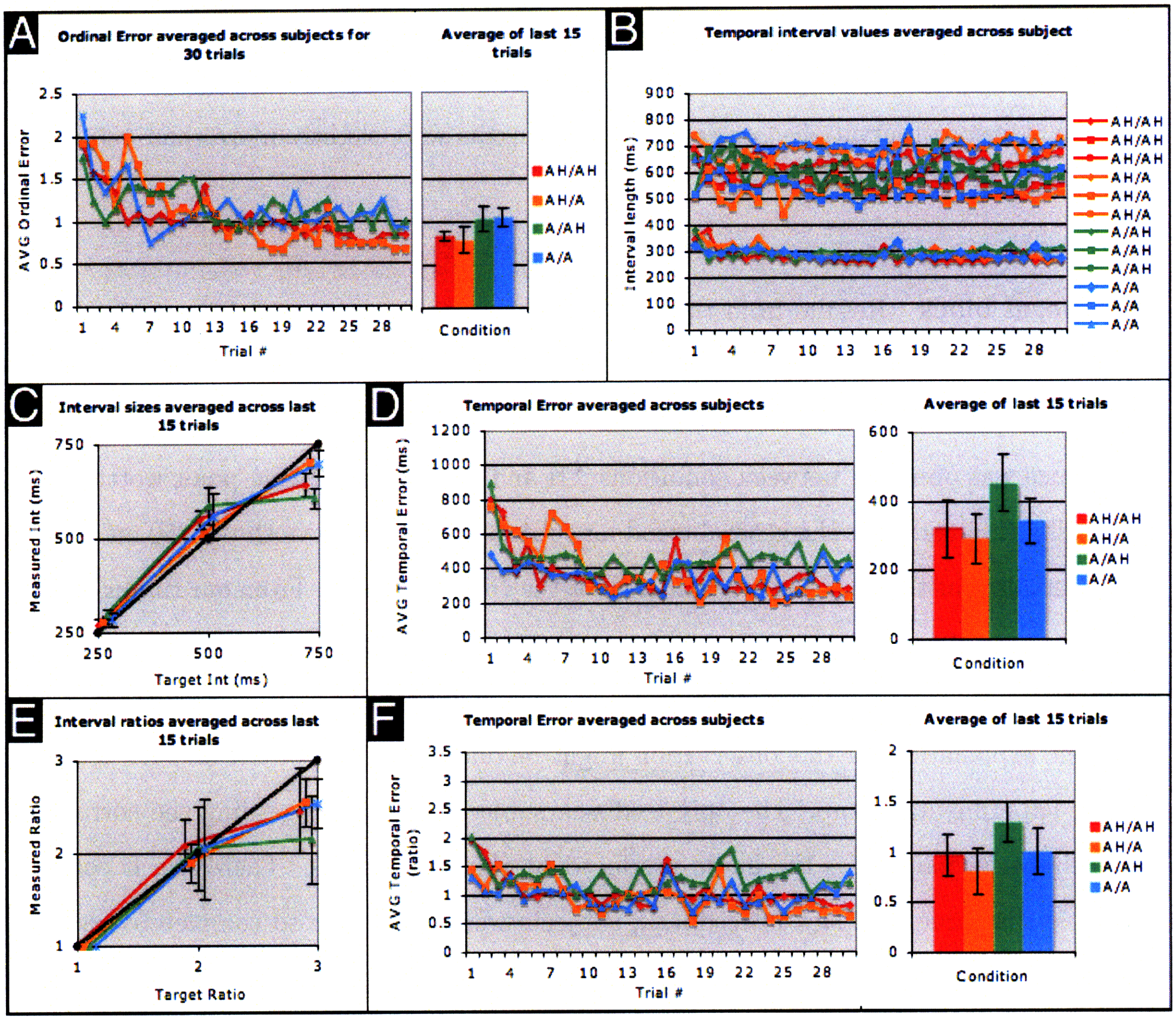

Figure 4-17: Experiment 3 Retention Block Results. Panel A shows ordinal error average across (N = 12) subjects and plotted by trial for each condition, along with a bar graph of the average of trials 16-30. Panel B shows measurements for each temporal interval in the sequence, averaged across subject and plotted by trial for each condition. Panels C-D show temporal data processed with respect to absolute timing, while panels E-F show temporal data processed with respect to ratio timing (see text for description). Error bars are standard deviation.

Ordinal block The results from the Experiment 3 Ordinal Block (Fig. 4-14A-B) follow the same trend seen during in the previous experiments: performance in condition AH resulted in the smallest amount of ordinal error (0.19), while condition A resulted in the highest error (1.28). Taken in combination with Experiment 1 and Experiment 2 Ordinal block, these data conclusively demonstrate the advantage of haptic guidance in an auditory-motor short-term memory task. Timing data from the Ordinal block (Fig. 4-14C-D) was similar to prior observations: average interval lengths were slightly more than 500 ms for all conditions (Fig. 4-14D).

Temporal block Results from the Temporal block of Experiment 3 (Fig. 4-15) did not indicate any significant differences between conditions in either the ordinal or temporal error analysis. These results replicate what we saw in the Experiment 2 Temporal block, where no difference was observed between conditions AH and A. One interesting point worth noting regarding timing data is the general trend for subjects to overshoot both the 250 ms and 500 ms intervals, but then consistently undershoot the 750 ms interval. From our timing data, it seems that subjects almost never overshoot the 750 ms interval, which is peculiar. Subjects overshoot both of the smaller temporal intervals, so why not the largest of the three? One possible explanation for this observation might be due to the lack of KR and KP feedback in the experimental setup. The only feedback subjects received regarding the correctness of their performance was the audio produced by their keypresses. Therefore, it could be possible that, due to a lack of feedback, subjects were never able to completely learn the length of the 750 ms interval. From the absolute timing analysis results (Fig. 4-15C), it is clear that subjects replicated the 750 ms interval as longer than the 500 ms interval, but from the ratio timing analysis (Fig. 4-15F), it is clear that, proportionately speaking, the 750 ms interval is always underestimated. Perhaps the lack of KR and KP feedback in this experimental setup facilitated a situation in which subjects were only able to retain a gross estimation of the 750 ms interval (they knew it was longer), but were not able to properly replicate its length (consistent underestimation).

Combined block In the Combined block, subjects learned 4 stimuli which varied in both time and note order. This experiment built on Experiment 2 Ordinal Block by providing two new conditions: AH/A, and A/AH, which were intended to test the effects of haptic guidance on ordinal and temporal transfer, independently. If ordinal error is lower for condition AH/A than for condition A/AH, then this lends more support towards ordinal learning being the type of learning that is most affected by haptic guidance, as seen in these experiments.

Results from the Combined block of Experiment 3 (Fig. 4-16) are somewhat surprising. Unlike Experiment 2 Combined block, the condition A/A resulted in an ordinal error measurement of 0.41, substantially less than the measurement of 1.56 for condition A in Experiment 2. One possible explanation might have to do with the different amounts of practice received during the Ordinal and Temporal blocks in Experiment 3. In Experiment 2, subjects executed three sequences under three conditions. In Experiment 3, subjects executed four sequences under two conditions. This meant that subjects had twice the amount of exposure to the learning conditions AH and A compared to Experiment 2. One hallmark of musical ability is the capacity to learn a musical passage by just listening to it. This is commonly referred to as having a "good ear" among musicians, and is characterized by an auditory acuity that enables one to replicate a tonal or rhythmic pattern after only listening to it. The musically naive subjects used in our experiment presumably would not have have a "good ear", or at least not as developed of an "ear" as a musician. The extra practice of the learning conditions during the Ordinal and Temporal blocks could have possibly aided these musically naive subjects in developing their "ear", and perhaps this development could have facilitated better transfer of the ordinal and temporal patterns learned under condition A. As for the remaining conditions, AH/AH and AH/A both resulted in equivalent ordinal error (0.91, 0.89), similar to condition AH in Exp. 2 Combined block, while condition A/AH resulted in a higher ordinal error (1.38) closer to that seen for conditions A & H in Exp. 2 Combined block. The measurements for conditions AH/AH, AH/A, and A/AH are in line with what was observed in Experiment 2.

Retention block Twelve subjects returned the next day to complete a Retention learning block, which was a repeat of the Combined block they had participated in the day before. Results from the Retention block of Experiment 3 (Fig. 4-17A) indicate slightly less ordinal error for conditions AH/AH (0.83) and AH/A (0.79) (the conditions with ordinal pattern trained in AH) than for conditions A/AH (1.04) and A/A (1.05). The results from conditions AH/AH, AH/A and A/AH maintain the trend seen in the Combined block. What is interesting from these data is the measurement of condition A/A: the lower ordinal error measurement seen for condition A/A in the Combined block is not replicated in the Retention block. Instead, condition A/A is equivalent with condition A/AH. The advantage of condition A/A in the Combined block seems to have completely washed out by the next day, as demonstrated by the elevated ordinal error measurement. This is quite an interesting result, since subjects are training on the same sequence which resulted in significantly lower ordinal error measurement the day before. Nevertheless, the result for conditions AH/AH and AH/A are still lower than condition A/AH (and now condition A/A). These results indicate that haptic guidance not only facilitates transfer, but that the transfer effect is lasting and retains to the next day.

4.5 Summary & Discussion

This chapter presented 3 experiments using the MaGKeyS Prototype to test how haptic guidance facilitates learning of rhythmic musical sequences.

In Experiment 1, three 10-note stimuli, which varied in both temporal and ordinal properties, were tested under three conditions: Audio + Haptic (AH), Audio (A), and Haptic (H). Given the relative difficulty of the sequences, only ordinal error was analyzed. We found that learning under condition AH resulted in the least amount of ordinal error, followed by condition H, and finally condition A.

Experiment 2 built on Experiment 1 in three ways. First, shorter stimuli, 6 notes in length, were used. Second, ordinal and temporal learning were assessed independently with separate learning blocks. Third, a transfer block comprised of stimuli that varied in both ordinal and temporal properties tested whether or not the effects of haptic guidance transfer to learning a new sequence.

The results from Experiment 2 Ordinal block are consistent with the pattern seen in Experiment 1: condition AH resulted in the smallest ordinal error, followed by condition H, and finally condition A. In the Temporal block, condition H resulted in slightly more temporal error than conditions AH and A, suggesting that haptic guidance did not provide any advantage over audio-only learning. In the Combined block, it was found that condition AH/AH resulted in significantly less ordinal error than conditions A/A & H/H. The haptic guidance advantage for condition H from the Ordinal block does not appear to transfer, as the measurement for condition H/H is equivalent with condition A/A. Furthermore, the advantage for condition A from the Temporal block does not appear to transfer, for the same reason. Only condition AH/AH results in less ordinal error, suggesting that the lower error measurements for condition AH in the prior blocks does transfer to better performance in the final block.

One of the questions not answered by Experiment 2 pertains to the "source" of the transfer advantage for condition AH/AH in the Combined block. Is this advantage due to learning the ordinal pattern under condition AH, learning the temporal pattern under condition AH, or both? To parse apart which component of the rhythm - ordinal or temporal - is contributing to the transfer advantage, Experiment 3 tested new stimuli in the Combined block: AH/A is a stimulus in which the ordinal pattern was trained under AH, but the temporal pattern trained under A, and A/AH is a stimulus in which the ordinal pattern was trained under A, and the temporal pattern trained under AH. Fig. 4-16A shows condition AH/A results in less ordinal error than conditions A/AH, suggesting that it is indeed ordinal learning which is primarily facilitated by haptic guidance and therefore drives the transfer effect. However, condition A/A in Experiment 3 Combined block exhibited a very low ordinal error value, unlike that observed in Experiment 2 Combined block. The origin of this result is unclear.

Experiment 3 also included a Retention session for 12 subjects the day after the initial session. In the results for the Retention session (Fig. 4-17A), conditions AH/AH and AH/A still result in less error than A/AH. However, condition A/A, unlike in the Combined block, now exhibits a higher measure, closer to the value seen for condition A/AH.

One cause for the unusual findings in Experiment 3 could be due to the higher amount of practice that the subjects are receiving in this experiment. In Experiment 2, subjects only test 3 rhythms in each block, and these are tested under different conditions in each of the composite blocks. However, in Experiment 3, subjects are testing each condition, A and AH, twice in each block. The repeated practice within a block of the same condition could possibly be one cause for the low results of the A/A measurement in Experiment 3 Combined block. One argument against haptic guidance is that it prevents people from learning on their own. One possible explanation for the lower error in condition A/A could be that the greater amount of practice under condition A in the Ordinal and Temporal blocks facilitated the subject's internal error correction mechanism, which was then engaged in the Combined block to provide better performance. The fact that this effect washes out by the next day, as seen with the Retention test, indicates that this effect it is not as consistent as the haptic guidance effect.

These experiments conclusively demonstrate that haptic guidance, as delivered via the electromagnetic keypress actuation of the MaGKeyS Prototype, facilitates rhythmic motor performance in an auditory-motor short-term memory task. Furthermore, these experiments strongly suggest that the advantageous effect of haptic guidance transfers into a general advantage in rhythmic learning.

As covered in the background, there is not an overwhelming body of evidence in favor of haptic guidance as an instructional method. So why do we now see what appears to be fairly clear evidence in favor of haptic guidance? I believe that this is largely due to the nature of the tasks and the perceptual modalities employed in these prior studies. In particular, the visual-motor tasks used by Feygin *et al.* [61] and Liu *et al.* [62] investigated how haptic guidance augments the visual system in providing information to guide a movement. However, in this study, we looked at how haptic guidance augments audio learning. The visual system is arguably the dominant sensory system employed in humans, and therefore it could be argued that haptic guidance should have a stronger effect augmenting audio learning than visual learning. If this is the case, then it would make sense that haptic guidance has a stronger effect in an audio-motor task than in a visual-motor task.

The clear effect of haptic guidance on ordinal learning is an exciting finding. However, we should not dismiss the possibility of haptic guidance facilitating temporal learning. Perhaps our experiment would have yielded a different finding for temporal learning had we used syncopated[6] rhythmic patterns. These patterns are often more difficult and less intuitive to learn than the simple temporal rhythms used in our study.

Another experimental paradigm that might elucidate an effect of haptic guidance for temporal learning is two-handed coordination. Subjects could first learn two different temporal patterns, one each for the two index fingers of the right and left hands. Then, subjects would attempt to learn to play these two temporal patterns simultaneously. Haptic guidance could be employed at either stage of learning. Such an experiment might reveal a useful effect of haptic guidance in facilitating coordination between the two limbs.

[6]Syncopation is a musical quality describing temporal patterns in which notes are shifted from occurring at regular "strong" metrical accents to instead occurring on irregular or "weaker" metrical accents.

Chapter 5

Application Development: MaGKeyS Trainer Piano

The third component of this thesis work involves the transfer of MagKeyS technology into a real-world application. The MaGKeyS Trainer Piano is a modified upright Baldwin^{TM}piano that contains electromagnets in the keys, similar to the MaGKeyS Prototype. This chapter covers the work done by myself and a team of MIT undergraduate researchers (UROPs) in fabricating and modifying this system. The work is split into two parts. The first part covers early work done in exploring fabrication of the custom electromagnets that would be required to implant into the keys of the piano, as well as the first methods of actuating a keypress. The second part covers the system we created for fabricating multiple size electromagnets, implementing these electromagnets into the piano, and modifying the keypress actuation to get a better feel out of the piano. This chapter ends with a short discussion of the future of this type of musical teaching device.

5.1 Exploratory Development

Figure 5-1 shows the work carried out on the piano from June 2007 - April 2008. This development comprised three elements: (1) Fabrication and installation of the electromagnet into the piano key, (2) Adding the ability for the computer to control keypress actuation, and (3) Designing two wrist cradles to aid in guiding the users hands to the correct keys. This initial development was planned as an exploratory phase, with the primary goal of prototyping the magnetic keypress actuation system in a small number of piano keys. Therefore, only 5 keys were modified: C2 (65 Hz) and G2 (98 Hz) for the left hand, and C4 (261 Hz), E4 (329 Hz) and G4 (392 Hz) for the right hand. This work was demonstrated at the April 2008 Media Lab Sponsor Week.

UROP team The initial UROP team consisted of Daniel Jang ('09, course 6) and Mitch Kelley ('11, course 2). Daniel worked on the project from June 2007 - May 2008. Mitch joined in January 2008 and worked through August 2008.

Electromagnets Fig. 5-1B shows the implanted electromagnet in a lower register key of the piano. Each electromagnet was fabricated by hand winding magnetic wire around a rectangular steel core, with two small pieces of acrylic glued to each end of the steel to hold the wires in place. The key was then carved out by hand, and the electromagnet was affixed using a high-temperature resistant silicon adhesive. The fabricated electromagnets were particularly large, measuring 2" x 1" x 0.75" and weighing over 1 lb. This additional weight at the proximal end of the key required us to mechanically compensate by attaching a spring to the underside of the key, just distal of the electromagnet (Fig. 5-1C, yellow arrow).

Keypress actuation Another issue we spent considerable time working on was how to actuate a keypress. In the MaGKeyS Prototype, keypress actuation is accomplished by fixing the electromagnet to the base of the keyboard and placing a movable 1/8" acrylic key above the electromagnet . When the electromagnet attracts the finger magnet in the Prototype, the 1/8" thick key is carried through a short displacement that actuates an electronic switch, thereby actuating a keypress in the system (see Fig. 1-1 for reference). In the piano, however, the electromagnet is fixed inside the piano key. Therefore, when the electromagnet attracts the finger magnet, it merely holds the finger to the key, but does not necessarily actuate a keypress. Another mechanism is needed to actuate the piano key. Using some spare solenoids we found around the lab, we accomplished piano keypress actuation by implanting solenoids on the underside of the distal end of the key (Fig. 5-1C, magenta arrow).

To control the electromagnets and solenoids in the piano, two of the custom PCB driver boards (described in Chapter 3) were connected to the Arduino USB prototype communication boards. The software was adapted to accommodate two communication ports, and the relative timing of the electromagnet and solenoid control signals were adjusted to account for the different delays in each actuation mechanism.

Wrist cradles The last element to be designed in this phase was a pair of wrist cradles (Fig. 5-1D) positioned in front of the keyboard. Since this early demo only involved 5 keys, we were able to use stationary cradles. The cradles were fabricated using ordinary steel rod and connector components, and affixing a felt-covered foam contour. Since these cradles are stationary, they are only a temporary solution. Nevertheless, these cradles proved to be an elegantly simple guide for helping users determine where to place their hands on the keyboard, at least for our limited demonstration. Once the users placed their wrists in the cradles and rested their hands on the keys, their fingers were close enough, usually within 1-2 inches from the target locations. This distance seemed to be small enough to accommodate rapid orientation of the user's fingers to the correct keys.

Initial public reaction The first incarnation of the MaGKeyS Trainer Piano was demonstrated at the MIT Media Lab's April 2008 Sponsor Week. Both medium and small sizes of gloves were outfitted with permanent magnets. The left-handed gloves contained two magnets, one in the pinky finger and one in the thumb, to map to keys C2 and G2, respectively. The right-handed gloves contained three magnets: one in the thumb, one in the middle finger, and one in the pinky finger, to map to the keys C4, E4, and G4, respectively. Participants, who were male and female adults, sat at the piano bench, put the gloves on, and placed their wrists in the cradles. The software then enacted a pulsing scheme in which the electromagnets in the five keys pulsed at a rate of roughly 500 Hz. These attractive pulses helped participants to adjust their finger to the correct keys. Once the fingers were positioned correctly, the software could then be triggered to play from an array of different songs. The user experienced the piano keys being automatically played, with their fingers attached to it. Overall, the majority of public reaction has been very enthusiastic about this project. When users first feel the piano keys draw their fingers down into a keypress, they often react with an expression of delight or wonder, and are often surprised by the experience. To date, an estimated 40-50 people have successfully demonstrated the piano.

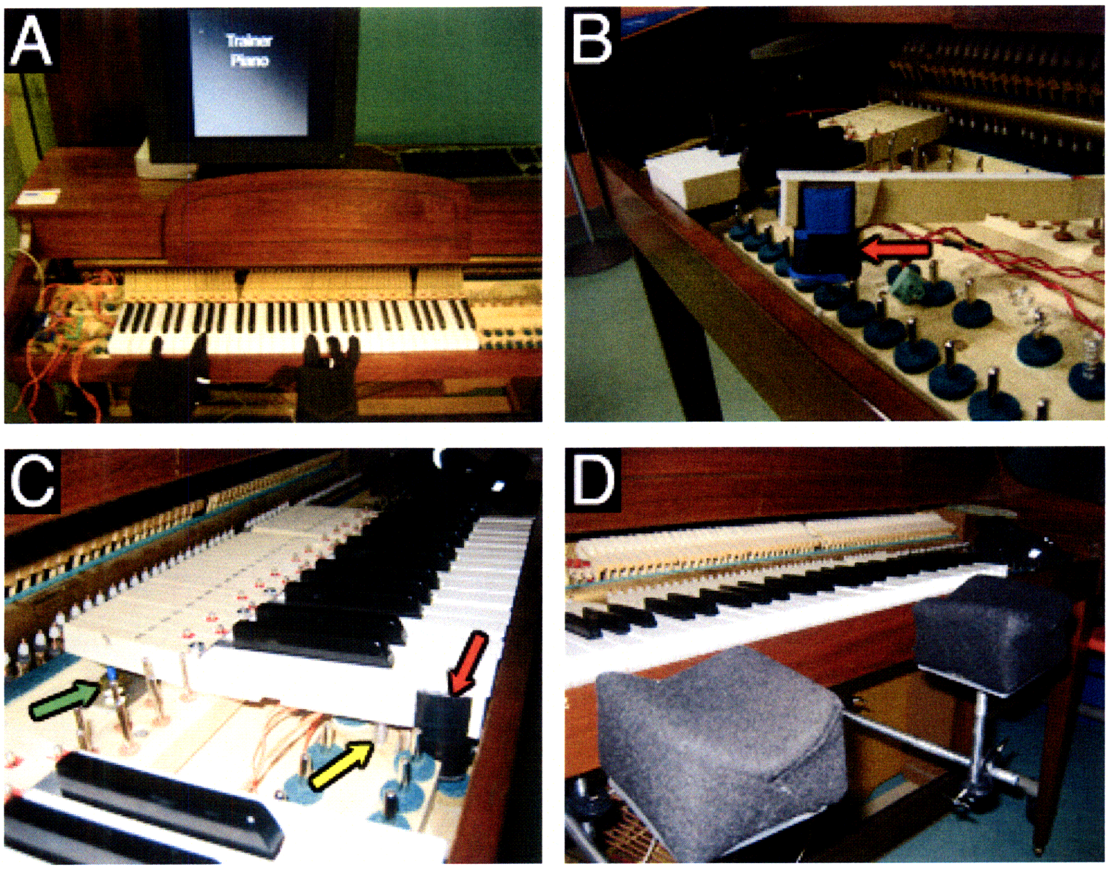

Figure 5-1: MaGKeyS Trainer Piano initial development. Five keys in the piano were outfitted with electromagnets (red arrow) and solenoids (magenta arrow). For each key, the electromagnet and solenoid acted in concert to attract the user's finger down into a keypress. A mechanical spring (yellow arrow) was used to compensate for the extra weight of the electromagnet. Felt-covered wrist cradles were positioned in front of the target keys to orient users.

5.2 Summer 2008: Scaling up the entire keyboard

During the Summer 2008 term, along with a team of 3 UROPs, we successfully fabricated and installed electromagnets into the entire keyboard. This work consisted of 5 parts: (1) Designing two electromagnets for installation into each key, (2) Electromagnet fabrication, (3) Devising a new keypress actuation scheme, (4) Adjusting the mechanical piano action, and (5) Modeling the piano in SolidWorks.

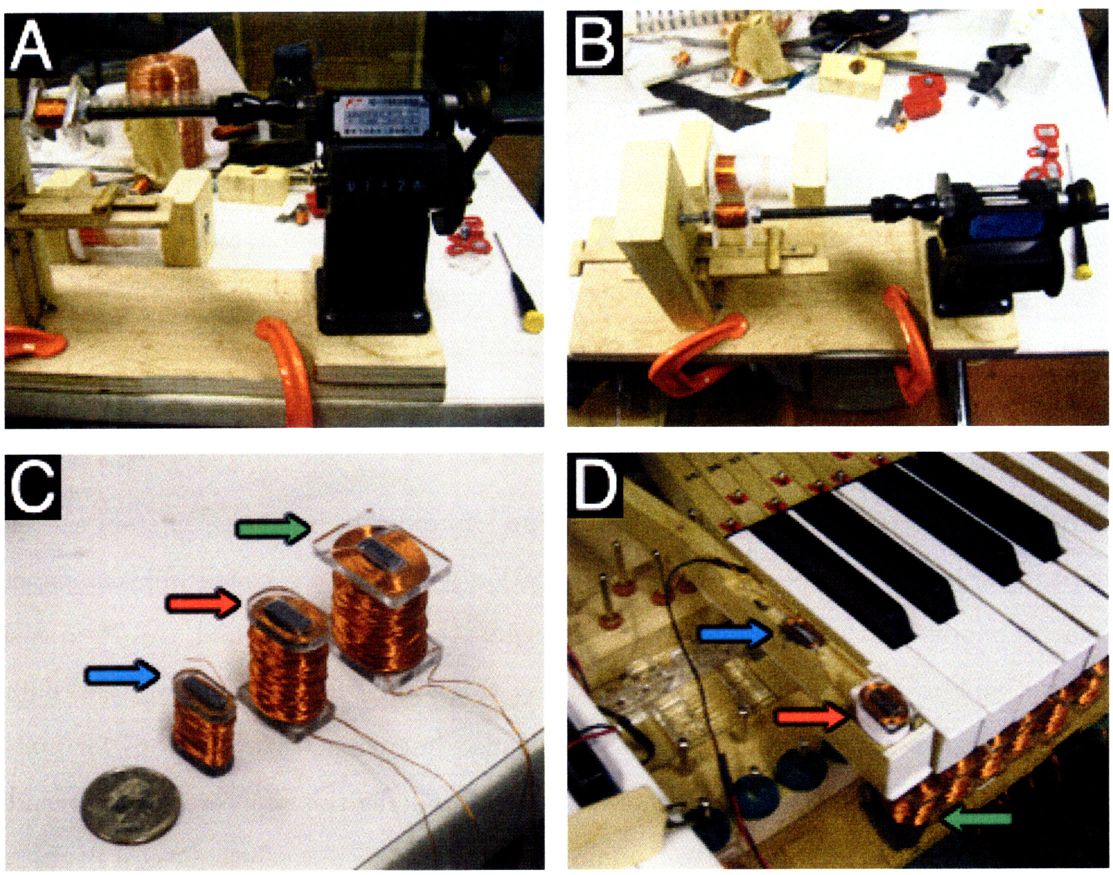

Figure 5-2: Electromagnet fabrication. A wooden support and mounting system was built to adapt to a hand-powered bobbine winder (A & B). The system was outfitted to accommodate different size electromagnets (C). The smaller electromagnets were used in the piano key (red and blue arrows), while the larger electromagnet was used to actuate a keypress (green arrow).

UROP team The UROP team for Summer 2008 consisted of Mitch Kelley ('11, course 2)., Jennifer Doyle ('09, course 2), and Adrian Dobson ('10, course 2).

Piano key electromagnets After the successful demo of the 5-key Trainer Piano at the April 2008 Sponsor Week, one of the observations we had was that having the electromagnet in only one position in the piano key does not allow for variable configurations in how the fingers contact the keys. For instance, a major triad, consisting of the keys C-E-G, is often played using the thumb, middle finger and pinky finger of the right hand. In the most comfortable configuration of this musical chord on the piano, the middle finger usually contacts the E key about halfway up the key, while the thumb and pinky are able to contact the key at the proximal end of the key, where the electromagnet is already installed. To try and compensate for this hurdle, we decided to use two electromagnets in each key: a larger electromagnet (Fig. 5-2C-D, red arrow) to be located at the proximal end of the key measuring 0.75" x 0.5" x 1" (L x W x H), similar to the 5-key version, and a slightly smaller electromagnet (Fig. 5-2C-D, blue arrow) to be implanted approximately halfway up the key, measuring 0.5" x 0.25" x 0.5" (L x W x H). The placement of both magnets into the piano key can be seen in Fig. 5-2D and Fig. 5-3C.

Electromagnet fabrication and installation In order to build the different size electromagnets, it was necessary to create a fabrication system with exchangeable components for accommodating the different size electromagnets we desired to build. An inexpensive Chinese bobbin winder was purchased on eBay (Fig. 5-2A) for $75, and we then built a small wooden mounting system, with spring loaded interchangeable end caps for mating different size electromagnets to the bobbin winder. By doing this, we were able to keep the cost of electromagnet fabrication to a minimum amount, which was just the cost of the raw materials (steel core, magnetic wire, and acrylic sheets). The three different sizes of electromagnets fabricated are shown in Fig. 5-2C. We ended up fabricating 180 electromagnets in total, 60 of each size.

The electromagnets were installed into the keys of the piano by using a mill to bore two cavities inside the piano key. The electromagnets were then installed into the piano keys using a high temperature resistant silicon adhesive. The electrical leads of the electromagnets were then soldered together, such that the two electromagnets in the key act as one electromagnet.

Keypress Actuation Due to the relatively high cost of commercially available solenoids, it was necessary to devise another keypress actuation scheme for the piano. Since we had developed a cheap way of making electromagnets (see prior paragraph), we decided on placing a further row of electromagnets, located underneath the proximal end of the key (see Figs. 5-2 C-D green arrow, and 5-3A and D). This electromagnet, when turned on, attracts the electromagnet located in the key above it, which then attracts the finger magnet. Adding this ability allowed for us to reduce the size of the piano key electromagnet, since adding another electromagnet to the keypress actuation axis (under the key electromagnet) only strengthens the magnetic flux for the whole axis. This electromagnet measured 1" x 0.75" x 1.25" (L x W x H).

Piano Action One of the most crucial aspects of working with the piano in this fashion has been the need to compensate for the additional weight in the piano key. In the earlier version, this was accomplished by using a spring underneath the proximal end of the key. The spring, however, is not an ideal choice: while a spring can compensate well for the extra weight in the system, the oscillatory energy introduced by the spring created a very unnatural piano action. Our choice of replacing this was lead weights threaded onto the rods attached to the end of the piano key (Fig. 5-3B). Each weight was then carefully reduced in size until the key to which it was attached demonstrated a piano action as close to original as possible.

Another compensation required was the repositioning of alignment pins underneath the piano keys. These alignment pins (see Fig. 5-3C, white arrow) are crucial for restraining the lateral sway of the piano keys during a keystroke. In an unmodified piano, the alignment pins are located at the proximal end of the piano key, in the same region where the electromagnet is installed in the piano key. In order to get around this problem, the row of alignment pins for the white keys on the piano was shifted 1/2" inch toward the fulcrum. In addition, the piano key alignment groove, which is located on the bottom side of the piano key, was extended to accommodate the new location of the alignment pin (Fig. 5-2C, yellow arrow).

Modeling of the piano In addition to all our fabrication work, Jennifer Doyle modeled the MagKeys Trainer Piano in SolidWorks (Fig. 5-4). The was done to partly help guide

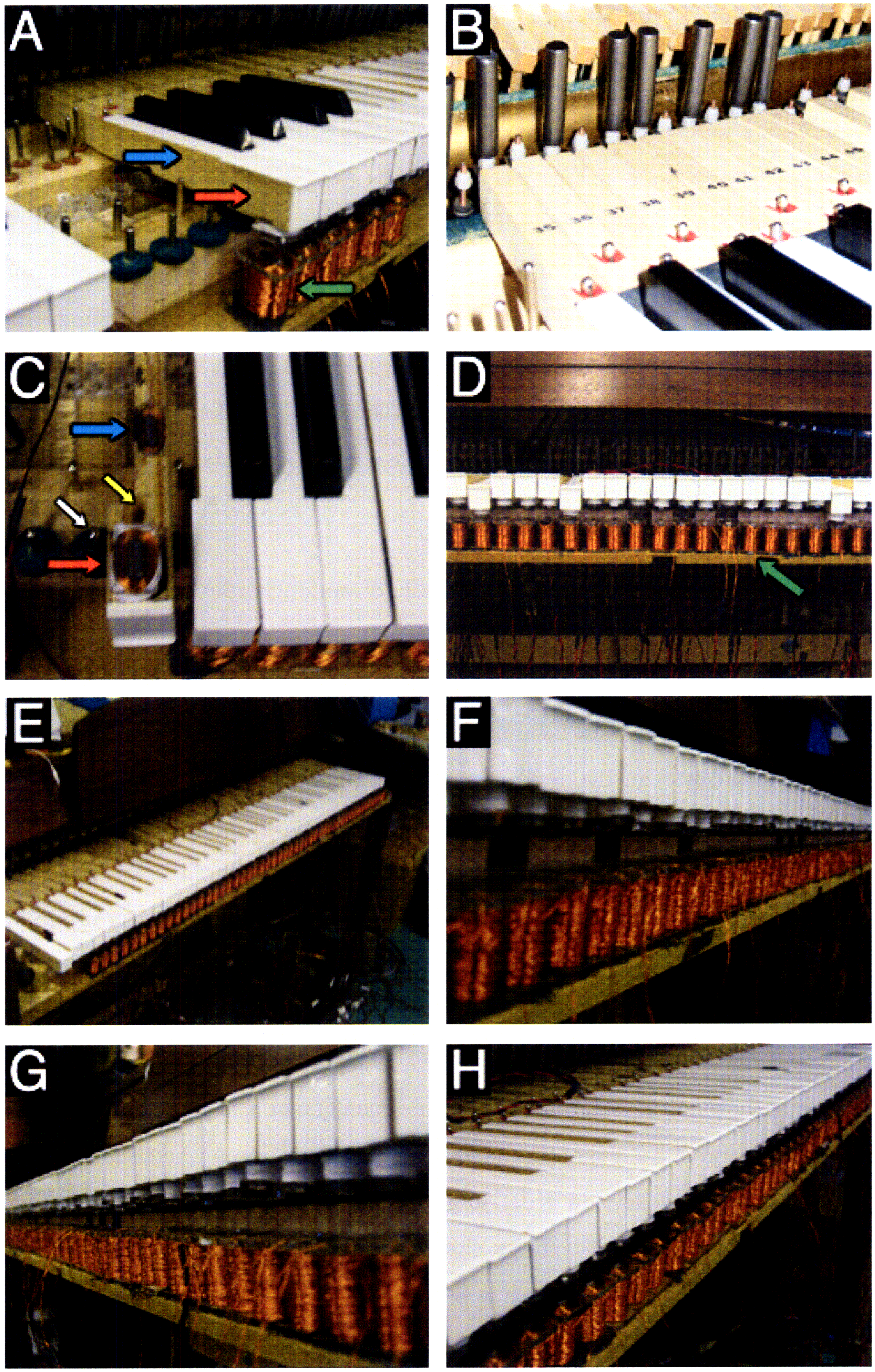

Figure 5-3: MagKeyS Trainer Piano. Blue and red arrows point to piano key electromagnets, green arrow points to keypress actuation electromagnet. Lead weights (B) were threaded onto the connecting rods at the distal end of the piano key to compensate for the additional weight of the electromagnets. White and yellow arrows point to alignment pin and alignment groove, respectively, both of which had to be shifted 0.5" towards the fulcrum in order to

us through the process of modifying the piano, while serving as a potential blueprint for future fabrications of this device.

Figure 5-4: SolidWorks model of MagKeyS Trainer Piano. The full keyboard, including electromagnets, alignment pins and counterweights, were modeled in SolidWorks. All images © 2008 Jennifer Doyle.

5.3 Future Direction

For further development of the MaGKeyS Trainer Piano, there are a few things we would like to keep in mind.

Sliding cradle system One of the most common questions asked about the piano is how we will enable lateral motion of the hands along the keyboard. Our answer to this is to develop a sliding cradle system for the wrists. This would be a passive system for restraining the user's wrists to lateral movement along the edge of the keyboard. This moving cradle system would be used in conjunction with a system of LEDs located just above the keys on the keyboard. The LEDs would operate in such a manner as to provide a visual cue to be perceived in the user's peripheral field of vision. Employing two 5-inch wide areas of light on the LED row, the program could signal to the user to approximate location of where their wrists should be along the keyboard. Then, it would be up to the user to relocate their hands to that place on the keyboard, with the help of the sliding cradle system. Once the cradles arrive at the correct location, a brake mechanism could be employed to hold the cradles in place.

Variable power/ Pulse Width Modulation electromagnetic system Another capability that would greatly enhance the system would be to upgrade the electronic control to allow for variable pulse-width modulation (PWM) control of the electromagnets. Differential control of the electromagnets in this fashion would allow for supplying different amounts of power the electromagnets, thereby affecting the motion of the keys. This feature could be used to not only provide different senses of "feel" in the way the electromagnets pull the fingers down to the keys, but could also be used to provide different dynamics of play in the way the large electromagnets cause the piano key to move. One observation we noticed with our bench power supply, was that reducing the amount of voltage caused the piano to play softer. Automating the voltage control could allow our system to have instant control of the piano's dynamics, a task that is not so easy with solenoids[1].

[1] The difficulty of achieving differential volume control with solenoid is due to their binary (on/off) actuation method. The center plunger of a solenoid usually does not move until the supply voltage is past a certain threshold, after which point the center plunger is forced to the other end. With the electromagnet, these is a much larger dynamic range of control to play with

Chapter 6

Summary & Discussion

In this thesis, we saw a new technology developed from idea to reality. MaGKeyS was embodied in both a prototype electromagnetic keyboard and in a full-scale piano. The prototype was used to validate the efficacy of the haptic guidance technology. In light of this, we look back at these three components and make some considerations on where to go from here.

6.1 Considerations

Prototype We saw the development of a low-cost, portable USB electromagnetic keyboard embodying MaGKeyS technology. Although this keyboard was only 5 keys for the right hand, a keyboard for both hands could be developed without much additional engineering. Such a keyboard would be very useful for running studies investigating two-handed coordination. Furthermore, such keyboards could be used by neuroscientists as a means of investigating sensorimotor learning. Such a device would also have vast potential as a rehabilitative tool. To date, no device exists to help facilitate differentiation of finger movements in patients with neurological hand paralysis.

Experiments In the body of experiments run in this thesis, we demonstrated that the combination of audio and haptic guidance facilitates the best performance for learning an ordinal sequence in an auditory-motor short term memory task. This result is very attractive. Prior work looking at haptic guidance has been sparse with strong results in favor of haptic guidance. This work, therefore, demonstrates a consistently verifiable experimental paradigm in which haptic guidance is seen to facilitate better performance in a motor task. This is a significant contribution to the field. This paradigm can now built upon to further elucidate the various manners in which haptic guidance can facilitate human motor learning.

The results from the transfer experiments (Experiments 2 & 3 Combined Blocks) were a little less clear. In Experiment 2, we saw that training on condition AH in the first two blocks results in better performance (in condition AH/AH) than training on condition A (in condition A/A). However, in Experiment 3, condition A/A resulted in the best performance, which came as a surprise. This cause for this result is unclear. The enhanced performance for condition A/A in Experiment 3 Combined Block could possibly be due to a general learning effect. Subjects tested on both experimental conditions (A & AH) twice in the Ordinal and Temporal blocks of Experiment 3. One possibility for explaining this interesting result could be that the extra practice of condition A in the first two blocks of Experiment 3 engaged a natural learning mechanism that facilitated better performance in the task during the Combined block. What is interesting, however, is that this advantage for condition A/A disappears by the next day, as seen with the Experiment 3 Retention Block. Speculations aside, it is clear from these results that the influence of haptic guidance on rhythmic motor learning is a rich field for future study.

Piano The MaGKeyS Trainer Piano represents the first application of MaGKeyS technology. As a pedagogical device, the Trainer Piano holds much promise. The next real step in the development will be to facilitate lateral movements along the length of the keyboard, presumably through a sliding cradle system. A Trainer Piano would be an attractive commercial product for many reasons, the primary being that so many people desire to learn the piano. During my two years at the Media Lab, I was able to demo the Trainer Piano, either as a concept or as a working demo, for many people, and I would frequently receive comments such as "This would be great for me...I always wanted to learn to play the piano." The piano is one of the most popular instruments in the world, and building a robotic tool to help people learn to play could be a huge commercial success. Furthermore, we could imagine in the future such pianos placed in senior homes and communities, providing the aging the population with a sensorimotor training and rehabilitation routine based around playing the piano.

Furthermore, the keypress actuation method developed for the Trainer Piano could represent a new mechanism for actuating piano keypresses in modern player pianos, such as the Yamaha Disklavier™series of player pianos. The current state of the art uses electromechanical solenoids, which have the disadvantage of a binary actuation method. In the Trainer Piano, the use of electromagnets allows for easily varying the dynamics of the piano keypresses. Therefore, the volume of actuated keypresses on the piano can be attenuated by adjusting the voltage knob on the power supply for the electromagnets.

6.2 Into the Future

This work comes at a time when noninvasive cognitive therapies are beginning to gain prominence as a means for maintaining cognitive health into old age[85]. The newly emerging market for these technologies is the cognitive and brain fitness market, which was estimated to be $225M in 2007 in the U.S. and growing at a 50 percent annual rate. As these therapy methods expand and develop, it is only natural that they will incorporate physical movement training and rehabilitation.

Both devices and experimental paradigm developed in this thesis represent a possible new avenue for developing physical devices for sensorimotor training and rehabilitation. The combination of ordinal and temporal learning involved in musical performance presents a perfect way to drive a rich sensorimotor experience for the user. Given that music is generally enjoyed by the majority of people, then we can imagine music an integral part to healthy aging.

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